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AN EVALUATION OF ELECTROOCULOGRAPHIC, HEAD MOVEMENT AND STEADY STATE EVOKED RESPONSE MEASURES OF WORKLOAD IN FLIGHT SIMULATION (U)

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

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The purpose of this research was to explicate the relationship between information processing demands and certain physiological indices during flight missions (low level ingress and tanker rendezvous) of varying levels of difficulty. A major focus was on the effect that availability of a light weight helmet-mounted display (HMD) system had on strategies of visual information intake.

Head and eye movement combinations, saccadic eye movements and blink characteristics were measured and analyzed. The feasibility of using steady state evoked potentials (SSEPs) of the brain (also referred to as "photic driving," or "driving") as an indicator of workload was also assessed.

Operational test pilots "flew" in a McDonnell-Douglas flight simulator adapted to resemble the handling characteristics and out-the-window view of a B-1B. (CONTINUED ON REVERSE)

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19. Abstract (continued):

The experimental paradigm consisted of four general conditions: Ingress/HMD, Ingress/no-HMD, Refuel/HMD, and Refuel/no-HMD. Within each of these conditions were four flights, each following a slightly different and unpredictable pattern; further, in some missions "threats" were introduced. The HMD was available during half of the missions; during remaining flights, information was presented in the traditional manner.

PREFACE

The work reported on herein was performed under contract number F33615-85-D-0514, Task 0013. This report, entitled "An Evaluation of Electrooculographic, Head Movement, and Steady State Evoked Response Measures of Workload in Flight Simulation," covers the period June 1986 through January 1988. This effort was performed by the Washington University Behavior Research Laboratory and the McDonnell Aircraft Company. Dr. John Stern and Dr. Robert Goldstein were the co-principal investigators. They were assisted by Douglas Dunham. The following members of the technical staff of the Advanced Design Group at the McDonnell Aircraft Company also participated in this effort, P. King, C. Arbak, B. Waldron, R. Jauer and E. Adam.

This task was conducted for the Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory through the Southeastern Center for Electrical Engineering Education under the technical direction of Mr. Michael Haas.

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A. INTRODUCTION

1.0 Objective

The objective of this project was to utilize visual steady-state evoked potentials (SSEP), head movements, eye movements, and eye blinks, to evaluate pilots' response to a helmet-mounted display (HMD) system devised to increase the efficiency of information input. Success in this effort would suggest, in addition, that these measures could be applicable as general psychophysiological measures of workload. The critical test of these measures was to take place in simulated flights with Air Force personnel.

With respect to the SSEP portion of the project, some preliminary work was necessary, first, to establish the phenomenon in a laboratory setting, second, to explore variables affecting the robustness of the effect, and finally, to apply these findings to determine optimal parameters for stimulation under flight simulation conditions. The preliminary experimentation was carried out in the Washington University Behavior Research Laboratory in St. Louis. The results of the preliminary laboratory work are summarized in Part B, Section 2.0.

2.0 Apparatus

The apparatus for the preliminary SSEP investigations was a masked oscilloscope (in earlier phases) and a light box (in later phases). These are described in Part B, Sections 2.1 and 2.7. The simulator and its environment, described in Appendix A, was a B-1 adaptation of a domed F-15 simulator located at the McDonnell-Douglas simulation facility in St. Louis.

3.0 Organization of Report

The substantive material in this report is divided into five sections:

In Section B, steady-state evoked responses are discussed. This includes a description if the preliminary work, the rationale for the selection of stimulation parameters, the procedures followed for the simulator runs, and the analysis and results of the SSEP data from these runs.

Section C contains the results of the analysis of saccades and blink data derived from the simulator runs.

Section D contains a review of the literature on head and eye movements.

In Section E, the results of a manual analysis of head movements during the simulation runs are presented.

Section F contains a qualitative and quantitative analysis of the relationship between head and eye movements during simulation.

B. STEADY-STATE EVOKED POTENTIALS ("PHOTIC DRIVING")

1.0 Purpose and Rationale

The purpose of this portion of the project is to determine the feasibility of using steady state evoked potentials (also referred to as "SSEPs", "photic driving" or, simply, "driving") of the brain as an indicator of workload. The rationale is based on the use of probe event-related potentials by Bauer, Goldstein, and Stern (1987) and SSEPs by Papanicoulaou (Papanicoulaou & Johnstone, 1984) to index the residual processing capacity of an individual involved in a task. In contrast to the "secondary task" method of assessing workload (e.g., Isreal, Chesney, Wickens, & Donchin, 1980), these methods are designed to minimize, if not eliminate, the active or passive participation of the subject in the assessment procedure.

The data suggest that the greater an individual's "involvement" in a cognitive task, the less residual capacity there is to process nontask material. Assuming that "involvement" is roughly translatable into workload, it would be predicted that the photic driving response to task-irrelevant flickering stimuli would decrease as a function of workload. Although the measure abstracted from the SSEP was somewhat different from that used here, Wilson and O'Donnell (1986) took an essentially similar position in their work. In the present application, the response of a pilot to light flashing imperceptibly would be expected to be inversely related to the degree of workload imposed upon him by various flight conditions. These flashes were to be delivered by flickering a helmet mounted display during simulated flight.

2.0 Summary of Laboratory Work Prior to Simulation Runs

2.1 In our initial efforts in the laboratory, the stimulus was presented on an oscilloscope masked so that a square approximately 32 mm per side was exposed.

The raw data went through several treatment stages. The spectral analysis output presented power in 1 Hz bins as a proportion of the total power from 0 to 100 Hz. This was done for two conditions, one a "control" and one a stimulation condition. In the second stage, the proportion of power at a given frequency under stimulation conditions was expressed as a percent change from the proportion under "control" conditions. In summary, it was found that:

1) there was evidence of a photic driving response in all subjects tested;
2) generally, flickering at lower frequencies (12, 18, and 24 Hz) produced driving of greater magnitude than did higher frequencies (40, 44, 48 Hz), though there was still substantial activity over and above

"control" levels; note that the higher frequencies were above the fusion threshold;

3) electrode placement was not a significant variable in determining driving. That is, O_1 and O_2 responded similarly to the stimulation;
4) over a one minute period, no consistent time effect was observed;
5) monocular stimulation produced photic driving levels comparable to those obtained under binocular conditions;
6) harmonic driving (driving at frequencies lower than the stimulating frequencies) was observed.

2.2 In an effort to reduce the number of stimulating frequencies to a more manageable set for data reduction purposes, and to retain the possibility of observing harmonic driving, the number of stimulating frequencies was reduced to four: 4, 8, 12, and 24 Hz. Results were

1) Individual differences existed with respect to the optimal frequency but the optimal level was consistent within subjects over several testing sessions.
2) There was temporal variability in the driving response for which we could not account. That is, it disappeared and reappeared in sequential samples.
3) Foveal stimulation was superior to peripheral stimulation (20° off center) in producing driving.
4) The question of whether a midline occipital or more lateral electrode location would be more effective in accommodating changes in fixation due to scanning in the operational setting was put to the test. Analyses of the O_z and O_1 output did not result in any significant differences. While it was decided to use the O_z location, the use of a more lateral electrode placement was not ruled out.

2.3 A large proportion of EEG activity occurs at frequencies below 20.5 Hz. There is a high potential for this activity to vary from segment to segment causing a fluctuation in total power. Since activity in all bins is expressed as a proportion of total power, this would have the effect of producing apparent variation in power in all other bins due to an unrelated shift in low frequency power.

Thus, we compared ouput of analyses which included power in the 0 - 20.5 Hz frequency range as part of total power with those that did not. In the process, the subject was flashed with a 50 Hz stimulus as an initial attempt to explore what happened at higher frequencies.

1) There was no apparent difference in driving indices based on the two measures of total power; nevertheless, it was decided to exclude the lower frequencies from total power in future measures to protect

against the possibility that this source of artifact might intrude under operational conditions not yet represented in the experimental paradigm.

2) There was evidence for driving at the higher (50 Hz) frequency, though it was more variable than at the lower frequencies used earlier. Further, the driving response was not observable in the first 10 s sample for this subject, a potential disadvantage.
3) No systematic effect of time was noted.

2.4 The effects of sinewave and squarewave modulated light were compared.

1) 24 Hz squarewave stimulation produced clear driving.
2) There was suggestive evidence for harmonic driving.
3) Again, no obvious time effect was observed.

2.5 A prototypical helmet with a reticle display was provided by AAMRL. The driving response produced by flickering the reticle display (squarewave at 24 Hz) was compared to the response produced by a 24 Hz, squarewave modulated light using a CRT display.

1) Both modes of stimulation produced driving. In fact, the CRT display appeared to produce more variable driving than the reticle display.
2) At 24 Hz, the subjects perceived the CRT display as flickering; this same frequency was perceived as a steady light by the same subjects when viewed via the reticle display. This was seen as a distinct advantage since it would be necessary to flicker the Kaiser helmet display at some (optimal) frequency above fusion threshold. And since we have seen that the driving response is generally greater at lower frequencies, this information was encouraging.

2.6 Up to this point the effect of time had not been evaluated formally. In order to do so, one subject was stimulated (at 24 Hz), using the reticle display, for three 4 minute blocks separated by 30 s periods of nonstimulation. (EEG from the nonstimulation periods were pooled and used as the "control" condition.)

1) Driving appeared in the initial time sample but rapidly deteriorated suggesting an habituation or fatigue effect.
2) Following each 30 s nonstimulation period, driving appeared to return, but, again, only briefly, reinforcing the suggestion made above.

2.7 This was the first time that a systematic time effect had been observed. To determine if this effect was due to stimulus intensity, a more intense stimulus was used. A light box, a cube, 14 in on each side with nine 7.5 W lamps evenly spaced in a 3 X 3 configuration on the inside back wall, was used to stimulate a subject at 24 Hz. The front of the box, a milky plastic sheet, was one foot from the subject's face. The illuminated sheet subtended an angle of 60°.

1) There was substantial driving across two 2 min stimulation periods with the exception of two unexplained 10 s chunks near the end of the second run.
2) When the number of lamps in the light box was reduced from nine to one, no clear time effect was seen. The subject in this condition was stimulated at 24, 30, and 40 Hz. At 24 and 40 Hz, there appeared to be an increase in driving over the period of stimulation, whereas at 30 Hz there was an initial increase followed by a decrease. At all three frequencies, thus, the initial measure was low, unlike at the higher intensity.

2.8 Since the angle subtended by the helmet mounted display was to be 12°, the effect of reducing the size of the field of stimulation from 60° to 12° was assessed using the same mode of stimulation (i.e., the 'light box', with one 7.5 W lamp). Further, since in the operational setting pilots would be scanning their environment, two laterally placed electrodes were added to explore the possibility that peripheral stimulation might be picked up more effectively by lateral electrodes. Two additional trials were tacked on to the end of this procedure in which the effect of rapid blinking was studied using large (60°) field stimulation.

1) Initial large field stimulation produced substantial driving at all electrode sites.
2) Reducing the size of the screen reduced the driving response by more than one half. Nonetheless, the response was still robust.
3) The spread of the driving effect to lateral electrodes, very strong in response to full field stimulation, was minimal in response to 12° stimulation. Lateral electrodes do not appear to be useful in detecting peripheral stimulation, at least at the sites used here (3 and 5 cm from the midline at the antero-posterior level of O_z).
4) There was a complete absence of driving at any electrode when the eyes were fixated 30° from center.
5) The effect of blinking was to reduce driving at all electrodes. The blink rate that produced this effect, however, far exceeded the normal level, but this still remains as a source of artifact, though minor.

3.0 Rationale for Selection of Parameters and Procedures

3.1 Frequency. The selection of stimulation frequencies was constrained by several requirements. Most important was that the subject would not be able to perceive flicker and, therefore, that the frequencies would have to be above the fusion threshold. A second reason for establishing the fusion threshold is the suggestive evidence in the literature (discussed in Sec 3.2) that optimal driving frequency is correlated with fusion threshold. Accordingly, choice of frequency, ideally, should be related to the fusion threshold, which differs across individuals. Since our accessibility to the pilots was limited to simulation time, it was necessary to establish the fusion threshold rapidly during that period. Time limitations in the simulator also precluded determination of individual optimal driving frequencies in any direct way. Consequently, selection of frequencies had to be made in a rather informal manner. That there were four flights (designated alpha, beta, charlie, and delta) in each of the four conditions (the conditions were HMD or noHMD, coupled with Ingress or Refuel) provided an *ad hoc* rationale for selecting four stimulating frequencies. The procedure for doing so is described below.

Another parametric decision implicit in the rationale presented above concerned the periods for which the stimuli were to be presented. Although the original intent was to flicker the display only at selected portions of the flight, several factors precluded this procedure, not least among which was the fact that flicker onset produced a perceivable drop in HMD intensity. For another, the manner in which a particular pilot flew a particular flight could not be specified *a priori* so there was no guarantee that introducing a stimulus at some fixed time in the flight plan would result in the same functional point for all pilots. Therefore, the simplest option appeared to be to turn the flicker on at a given frequency at the beginning of a flight and off at the end.

3.2 Intensity. Early work is abundantly clear in indicating that stimulus intensity is positively correlated with fusion threshold (Hecht & Shlaer, 1936). Other data (Simonson & Blankstein, 1961) suggest a correlation of fusion threshold with maximum driving frequency. Unfortunately, there was only limited control that could be exercised in the present effort over this potentially important parameter. HMD intensity was under the pilot's control via an uncalibrated potentiometer. The pilots had been informally instructed to turn up the intensity to a level that was "comfortable", but this level could not be measured independently.

3.3 Waveshape. Although our early lab work was based on the assumption that the waveshape would be square, the actual state of affairs was more complex than that, and depended, in part, on the time it took to repaint the screen in each pass. In a spectral analysis of the HMD signal picked up at the rear cockpit, it was found that the percent of total activity found at the nominal stimulating frequency was never greater than 74% and was as low as 33%. The remainder was spread across the spectrum with consistent secondary peaks, showing as much as 15% power, at other frequencies. Further, more often than not, the frequency exhibiting the greatest power was not the nominal stimulus frequency but usually 1 Hz higher.

3.4 Control for Stimulus Artifact. In laboratory sessions preliminary to the formal flight simulation tests with the pilots, subjects underwent flickering with eyes closed. It was discovered that the stimulation induced a nonphysiological "coupling" artifact in the EEG circuit. We assumed that the source of this was the HMD generator at the rear of the helmet, which was in close proximity to the EEG electrode. The data suggested, nevertheless, that response power at the critical frequency was greater when the eyes were open than when closed, so that the contribution of the brain's processing to the output could still be evaluated. This required the inclusion of an eyes closed and eyes open control for each frequency used. Since the artifact would be expected to appear in the record under both eyes closed and eyes open conditions, the difference in the EEG record under these conditions could be interpreted as activity generated in the brain in response to the flicker.

4.0 General Simulation Procedure

A description of the method of adaptation of the F-15E cockpit to simulate a B-1 environment, the cockpit displays, and the helmet mounted display systems, are presented in Appendix A. These are based on a description provided by McDonnell-Douglas.

4.1 Electrode Application. Seven electrodes were attached to each pilot. Four electrodes were used for EOG recording: one each above and below the right eye for recording of blinks and vertical eye movements, and one each lateral to each eye, for the recording of horizontal eye movements. For EEG recording, one electrode was applied at O_z and one to ear as reference. A ground electrode on the forehead completed the array. The pilot was then brought into the simulator and the helmet was put on.

4.2 Calibration. A period of recording followed to ensure the integrity of the recording system. To calibrate the eye movement system, the pilot was asked to fixate calibration points located on the dome display 10° and 45° laterally in each direction, and 10° vertically in each direction.

4.3 Stimulation Frequency. The first step in selecting frequencies was to establish the fusion threshold. This

was done through a modified up-and-down procedure. The HMD was flickered at a rate determined, a priori, to be below any pilot's fusion threshold. The pilot was asked to report whether he perceived flicker. If so, and all did at this level, the flicker frequency was increased in 4 Hz steps until he reported fusion. At this point, the procedure was reversed; the frequency was lowered, halving the step interval to 2 Hz, until he again reported flickering. The fusion threshold (cff) was defined as the average of these reversal points. Of the four frequencies for each pilot, the lowest frequency was 4 Hz above this average, and the remaining three were at additional 4 Hz increments. (The one exception to this procedure occurred when one pilot's cff was so high, following the above formula, that the highest frequency for him would have been within range of the 60 Hz filters. The range of his frequencies was compressed so that the highest one was not above 54 Hz.) These points were recorded on a form exhibited in Figure 1.
This overall procedure was designed to sample a broad range of frequencies and seemed the best of our options in locating the optimal frequency for each subject.

4.4 Order of Flight Conditions. As seen in Figure 1, a combination of two variables (HMD vs. noHMD, and Refuel vs. Ingress flights) produced four general conditions. The order of the conditions for each pilot differed, although all pilots started with an ingress mission, either HMD or noHMD, and continuing with ingress, went from HMD to noHMD (or reverse) before switching to the refuel flights. Thus, subject 1 would go from Ingress/HMD to Ingress/noHMD and then from Refuel/noHMD to Refuel/HMD. For Subject 2, the order was: Ing/noHMD, Ing/HMD, Ref/HMD, Ref/noHMD. Further, for each of these four display-mode/mission-type conditions, there were four flights, each differing somewhat from the others in that condition. The flights were ordered differently within each condition and were run with only enough interruption to set up the next flight in the computer and take SWAT ratings. After each of the four conditions, there was an additional brief delay to change recording tapes and run a nonflight control (described in Sec 4.5), when that was called for.

4.5 Nonflight Stimulation Control. An eyes-closed and an eyes-open control condition were introduced prior to and following each of the two HMD conditions (Ingress and Refueling.) While alert and looking straight at the HMD, each subject was given a half minute of flickering with his eyes closed followed by a half minute of eyes-open flickering. The frequency used in each test was that used in the upcoming flight (if the flight was the first in the condition), or in the immediately prior flight (if the flight was the last in the condition.) In this way, a

HMD PROJECT - PILOT SIMULATION DATA

ESTABLISHING eff		FREQUENCIES			
going up	______	A	______	Date	______
going down	______	B	______	Tape #	______
Fusion Point	______	C	______	Pilot	______
		D	______		

TIME CODE STARTED: ______

SWAT CODE: time (1 - 3) / mental (1 - 3) / stress (1 - 3)

1 - INGRESS TAPE # ____ HMD

EYES CLOSED ______ EYES OPEN ______

flight type	frequency	swat

2 - INGRESS TAPE # ____ NO HMD

flight type	swat

3 - REFUEL TAPE # ____ NO HMD

flight type	swat

4 - REFUEL TAPE # ____ HMD

EYES CLOSED ______ EYES OPEN ______

flight type	frequency	swat

CALIBRATION

Veritcal EOG	______
Horizontal EOG	______
Vertical Head Mvmt	______
Horizontal Head Mvmt	______

CHANNEL ASSIGNMENT

Vertical EOG	______
Horizontal EOG	______
EEG	______
Veritcal Head Mvmt	______
Horizontal Head Mvmt	______
Stimulus Artifact	______
Voice	______
Time Code Generator	______

Figure 1

nonflight control sample was obtained for each frequency. Time restrictions prohibited including such eyes-open/eyes-closed controls at the beginning and end of each flight.

4.6 Data Recording. Eight channels of data were tape recorded: Vertical EOG, Horizontal EOG, EEG (O_z), Vertical Head movement, Horizontal Head movement, Stimulus artifact (flicker), Voice communication between controllers and pilot, and Time code.

5.0 Data Reduction (All data were digitized at a sampling interval of 5 ms)

5.1 Spectral analysis. Our spectral analysis (FFT) program operates on samples 10.24 s in duration, and was set to express the power in 1 Hz wide bins from 0 to 55.5 Hz. In addition, total power from 0 to 100 Hz was determined for each sample.

5.2 Treatment of Spectral Analysis Output. The power in each frequency bin was expressed, in earlier work, in two ways: as a log change of power compared to that in selected neighboring bins, and as a percent of total power (from 0 to 100 Hz). The latter proved to be reliable and essentially redundant with the log measure, so the data reported here will be restricted to the percent measure. Further, since we anticipated the possibility of considerable variation in energy at low frequencies from condition to condition, variation that we did not want to contribute artifactually to our percent measure, we redefined total power to exclude that below 20.5 Hz. In summary, then, the power in a 1 Hz bin was expressed as a percent of all activity from 20.5 to 100 Hz.

The percent values described above were carried one step further. The frequency in every test condition was compared with that in an appropriate baseline condition (the base condition will be identified in every case). The baseline percent was subtracted from the test percent. To identify the source of the contributions to the difference scores, in later analyses, however, the percent power in each condition was presented without subtracting a baseline.

5.3 Data Selection Strategy. For each of the four pilots for whom we had a readable EEG record, an evaluation was made as to whether he showed evidence of photic driving. Frequency analysis output during the nonflight eyes-open condition was compared to the appropriate baseline: the frequency pattern during the nonflight eyes-closed condition. A positive value for this statistic (test minus base) was taken to indicate that the brain response to the stimulating frequency was over and above any

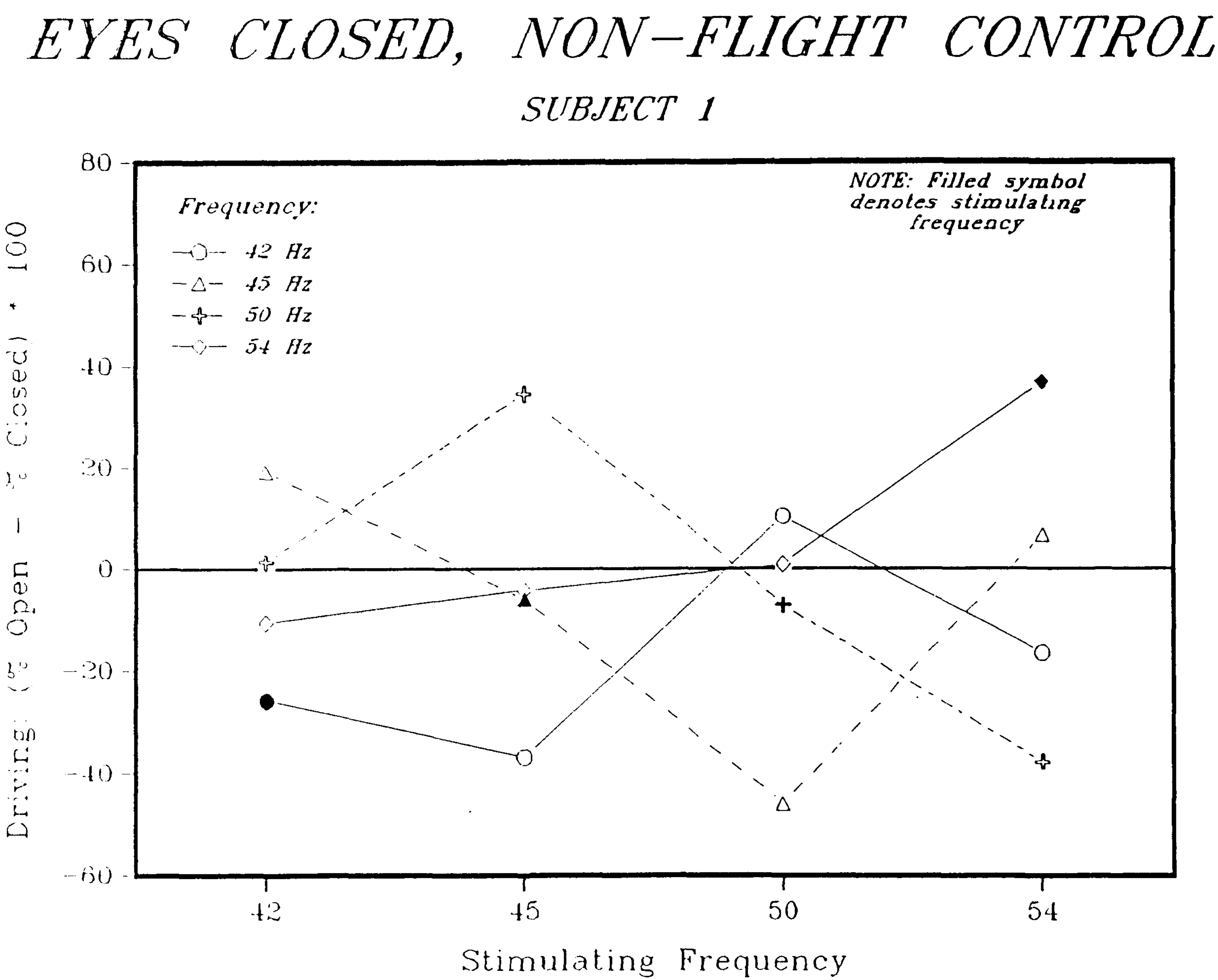
artifact induced in the electrode circuit by the stimulus source. This was done for each of the four frequencies for each subject.
The criterion established for further analysis for any subject was that the increase, from base to stimulation conditions, at a particular <u>stimulated</u> frequency, had to exceed, by some acceptable amount, the change in that same frequency when it was the unstimulated frequency in the three other stimulation tests. Thus, for example, if A, B, C, and D frequencies were used for subject 1, and we were evaluating his response to frequency D, his percent of total power at D under eyes-closed conditions would be subtracted from his percent at D in the eyes-open condition. The criterion for continued analysis for this subject, then, would be that this difference would have to exceed the similarly derived values for frequency D when frequencies A, B, and C were the stimulating frequencies.

If the above criterion was met, we went on to digitize and spectrally analyze that subject's data for those two flights, one ingress and one refuel, for which he was flickered at that frequency. It should be noted that in the latter analyses, the base condition was changed from the eyes-closed condition, used in the above evaluation, to the eyes-open condition. Activity at a given frequency in the eyes-open nonflight condition was subtracted from the activity at that frequency during the flight segment being evaluated. Thus, a non-zero value would be obtained only if simulated flying altered activity that was produced in the alert, but non-flight, condition. This treatment assumes that the non-flight condition is essentially a zero workload condition.

6.0 Results

6.1 <u>Nonflight Eyes-open/Eyes-closed Comparisons</u>. Figures 2 to 5 depict the results of the initial analyses of the nonflight diagnostic control for the four subjects. For each subject there are four sets of four frequencies, each set (a 'set' comprises the points in a column above the frequency designation on the abscissa) corresponding to one of the stimulating frequencies. Within each set, the darkened symbol indicates the value for the stimulation frequency. The other three points in that set represent the change at the remaining frequencies when stimulation was at the frequency designated in the legend.

The activity increase as a function of stimulation can be determined for a given frequency, by comparing output at that frequency, when it was the stimulation frequency (darkened symbol), to the output when it was not the stimulation frequency, the remaining three open symbols



EYES CLOSED, NON-FLIGHT CONTROL
SUBJECT 1
Frequency:
42 Hz
45 Hz
50 Hz
54 Hz
NOTE: Filled symbol denotes stimulating frequency
80
60
40
20
0
-20
-40
-60
Driving (% Open - % Closed) * 100
42
45
50
54
Stimulating Frequency

Figure 2

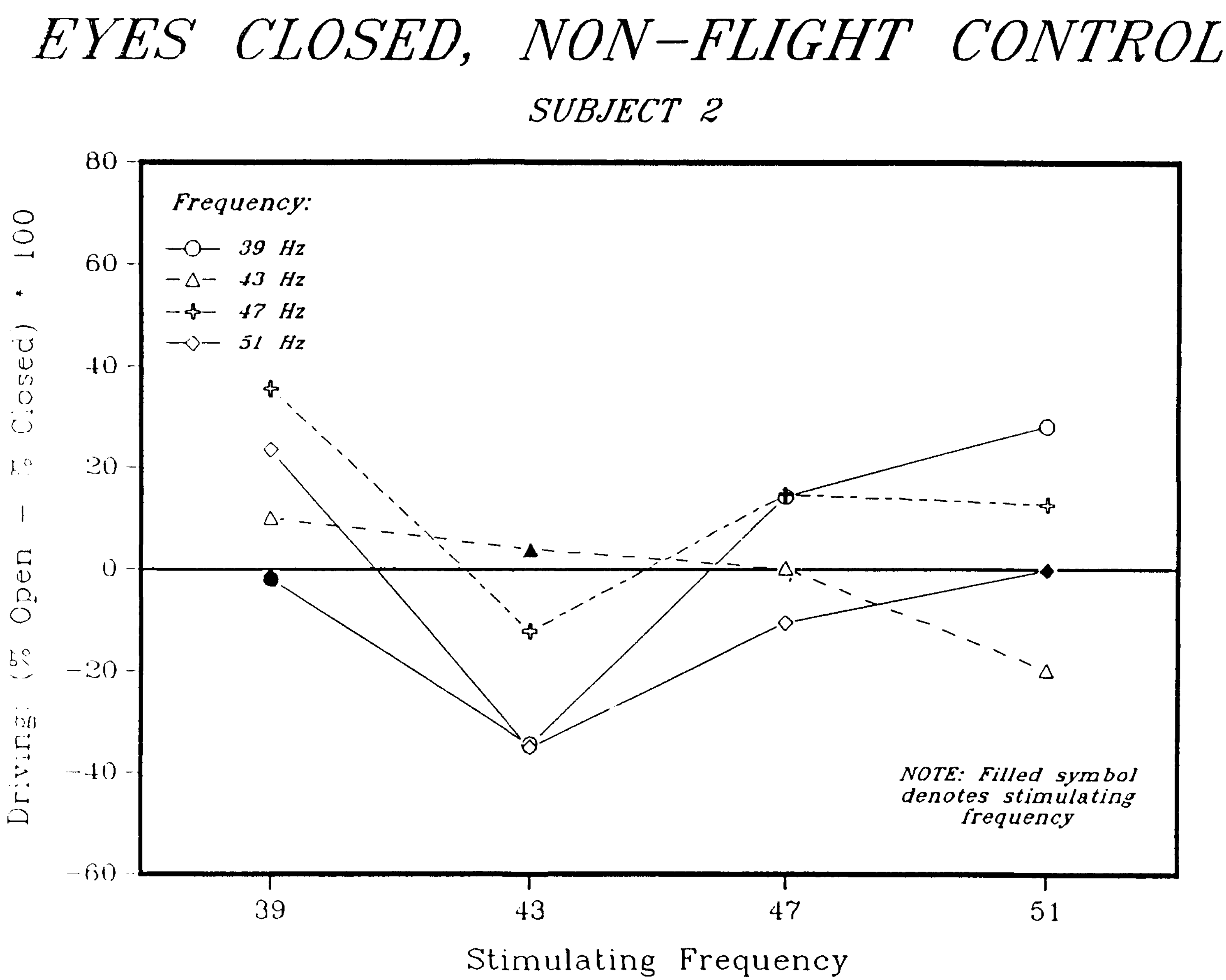

EYES CLOSED, NON-FLIGHT CONTROL
SUBJECT 2
Frequency:
39 Hz
43 Hz
47 Hz
51 Hz
NOTE: Filled symbol denotes stimulating frequency
80
60
40
20
0
-20
-40
-60
Driving (% Open - % Closed) * 100
39
43
47
51
Stimulating Frequency

Figure 3

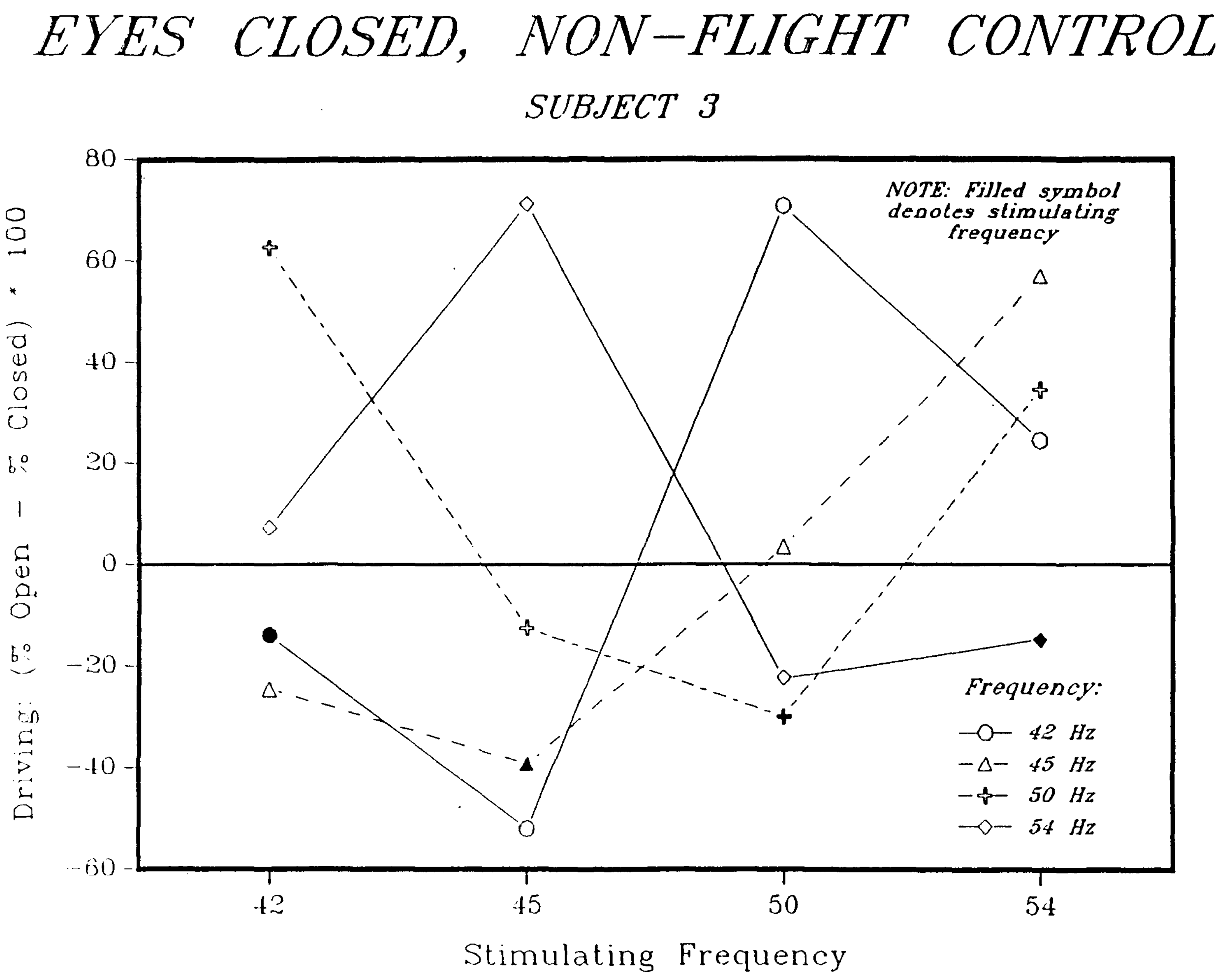

EYES CLOSED, NON-FLIGHT CONTROL
SUBJECT 3
NOTE: Filled symbol denotes stimulating frequency
Frequency:
42 Hz
45 Hz
50 Hz
54 Hz
80
60
40
20
0
-20
-40
-60
Driving: (% Open - % Closed) * 100
42
45
50
54
Stimulating Frequency

Figure 4

EYES CLOSED, NON-FLIGHT CONTROL

SUBJECT 4

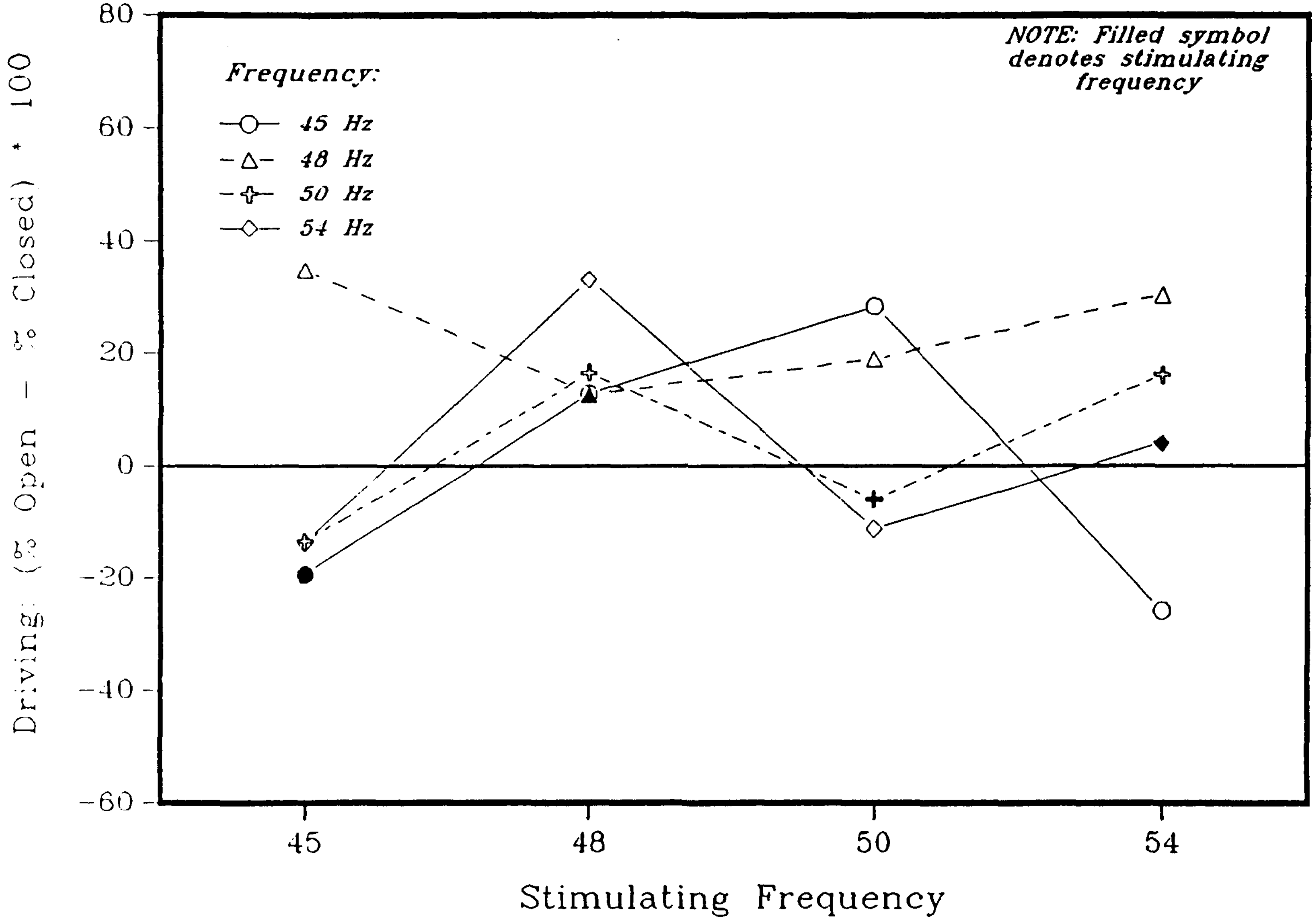


Figure 5

connected to that darkened symbol. Accordingly, it can be seen in Figure 2 that for subject 1, the criterion for photic driving was met by a single frequency: 54 Hz. The filled symbol at 54 Hz was above the connected open diamonds; the latter represent the output at 54 Hz when the stimulating frequencies were 42, 45, and 50 Hz. In no other case was the criterion met; for example, for 45 Hz, the percent power increase at 45 Hz, when stimulation was at 42 or 54 Hz (cf., triangles, first and fourth sets), were greater than the increase at 45 when 45 was the stimulation frequency (filled triangle, second set), thus ruling out 45 Hz as a criterion frequency.

Figure 3 displays the data for Subject 2. The data are unconvincing in demonstrating evidence of driving. The only frequency that approached the criterion was 43 Hz and in that case the activity at 43, when the stimulating frequency was 39 Hz, was somewhat higher than that at 43, when 43 was the stimulating frequency.

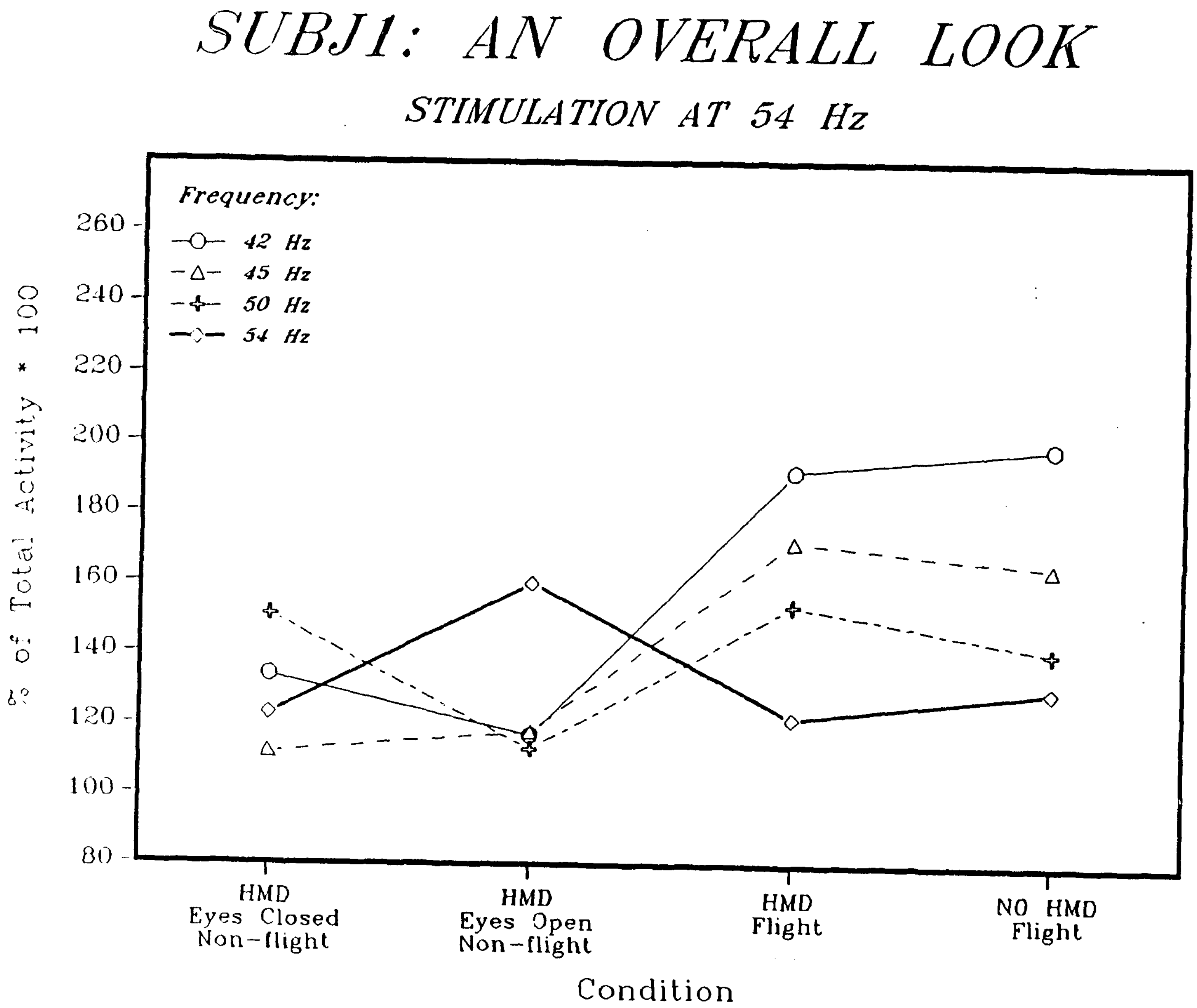
Neither of the remaining two subjects showed evidence of meeting the criterion, as can be seen in Figures 4 and 5.

In summary, only one subject, and he at only one frequency, 54 Hz, met our criterion for follow-up analysis. The following is based on subject 1 only and only at this frequency.

6.2 Subject 1: Overview of Output at Selected Frequencies. It should be emphasized, at the outset, that the following observations are based on a limited number of samples from only one subject. The observations offered should be accepted with this in mind. It is our view that the strength of the interpretations lies in the coherence of the various patterns exhibited in different conditions.

Prior to viewing the effects of events within a flight on the driving response, we present an overview, in Figure 6, of the effects of the general simulation conditions on output at the four frequencies for subject 1. The data for each condition are in terms of the power at a given frequency expressed as a percent of total power ("total power" is defined as activity above 20 Hz) in that condition. Four conditions are plotted: the first two are the nonflight eyes-closed and nonflight eyes-open conditions, both with the flickering HMD. The third condition is the average of the first half minute for the ingress and refuel HMD delta flights (the 54 Hz flights). The last point represents the averages for the same periods in the noHMD (non-flickering) condition.

It will be recalled that the differences between the first two conditions have already been presented in Figure 2 as the data displayed above the 54 Hz point on



SUBJ1: AN OVERALL LOOK
STIMULATION AT 54 Hz
Frequency:
42 Hz
45 Hz
50 Hz
54 Hz
260
240
220
200
180
160
140
120
100
80
% of Total Activity * 100
HMD Eyes Closed Non-flight
HMD Eyes Open Non-flight
HMD Flight
NO HMD Flight
Condition

Figure 6

the abscissa. Figure 6 illustrates that the difference in percent of total power at the stimulating frequency, observed in Figure 2, was not due to a particularly low initial point but to a real increase when the eyes were opened. The power for the four nonstimulated frequencies, in contrast, either decreased or remained unaffected. The change, moving from the second to the third point, represents the effect of increasing the workload from minimal (nonflight, condition 2) to some moderate level at flight onset. Here we see an increase in all nonstimulated frequencies while the power at 54 Hz decreases. This pattern is consistent with the hypothesis that an increase in the imposed workload produces a reduction in the capacity of the brain to process task-irrelevant information. Why the remaining frequencies exhibited an increase in power, which, by contrast, was substantial, is not clear at this point.

Explanation of the factors determining the final condition (NoHMD) is a bit more complex. In this phase, the pilot has the same assigned task as in the analogous HMD flight condition, but is not being flickered, and, in fact, does not have the HMD available. The difference, therefore, would have to be due to the flickering plus any workload difference. Since the workload level, as minimal as it might have been in condition 3, was hypothesized to have already reduced responsiveness to the flicker, we have little reason to expect that condition 4 would substantially modify that. In the ideal case, of course, we would hope that the 54 Hz output in condition 4 would be lower than that in condition 3. That is, the workload in condition 3 was judged to be only minimal and therefore, following the argument above, it would be predicted that the subject would still retain some residual capacity to process the flickering stimulus. The present results do not allow much room for further depression of output in condition 3 in periods within that flight (reported below) when load was judged to be higher than at flight outset. Nevertheless, activity in condition 4 was almost identical to that in the nonload (first) condition; this would suggest that at the outset of condition 4, we are observing a normal EEG pattern. Since the 54 Hz output in condition 1 differed little from this level, it would appear that little, if any, coupling artifact was produced by flickering a pilot whose eyes were closed.

The points plotted in condition 3, Figure 6, represented the average of the opening segments of 54 Hz ingress and refuel flights. We turn now to an investigation of the events occurring within these flights.

6.3 Ingress Flight Delta.

6.3.1 Flight plan. The flight plan for the criterion ingress flight (flickered at 54 Hz) is presented in Figure 7. Waypoints are indicated on the plan by circled numbers. The flight is broken up into segments, indicated by numbers 1 to 11, that correspond to the periods subjected to spectral analysis.

6.3.2 Within Flight Workload Estimates. Since there were no threats introduced in this flight, the course of the flight was rather homogeneous from a workload perspective. We could speculate, nevertheless, that in the initial periods (#1 and #2) the workload is relatively low. Though the period just before waypoint 2 might have usefulness as a higher workload segment, since a turn was required, the EEG record for that period was contaminated by artifact, precluding analysis of this data segment.

Speculating further about workload variation within the flight, it would not be unreasonable to suppose that workload would be higher during the turn executed between waypoints 2 and 3 than in the straightaway following waypoint 3. These estimates are summarized in Table 1. Note that the workload category descriptors are chosen to be consistent with those in Table 2 below.

Table 1

Workload Estimates for Segments of Ingress Flight Delta for Subject 1

Workload Estimate	Flight Segment
Low	1, 2
Low +	7,8,9,10,11
Medium	3,4,5,6

As can be seen in Figure 8, there does not appear to be any relationship between the estimated workload level and modulation of the power at 54 Hz, or, for that matter, at any of the four frequencies.

6.4 Refuel Flight Delta

6.4.1 Flight Plan. The flight plan for refuel flight delta is presented in Figure 9. The typical refuel flight routed the tanker on a U-shaped course, the bomber approaching from the opposite direction. Several variations of this pattern were introduced to prevent anticipation of upcoming events. In the case

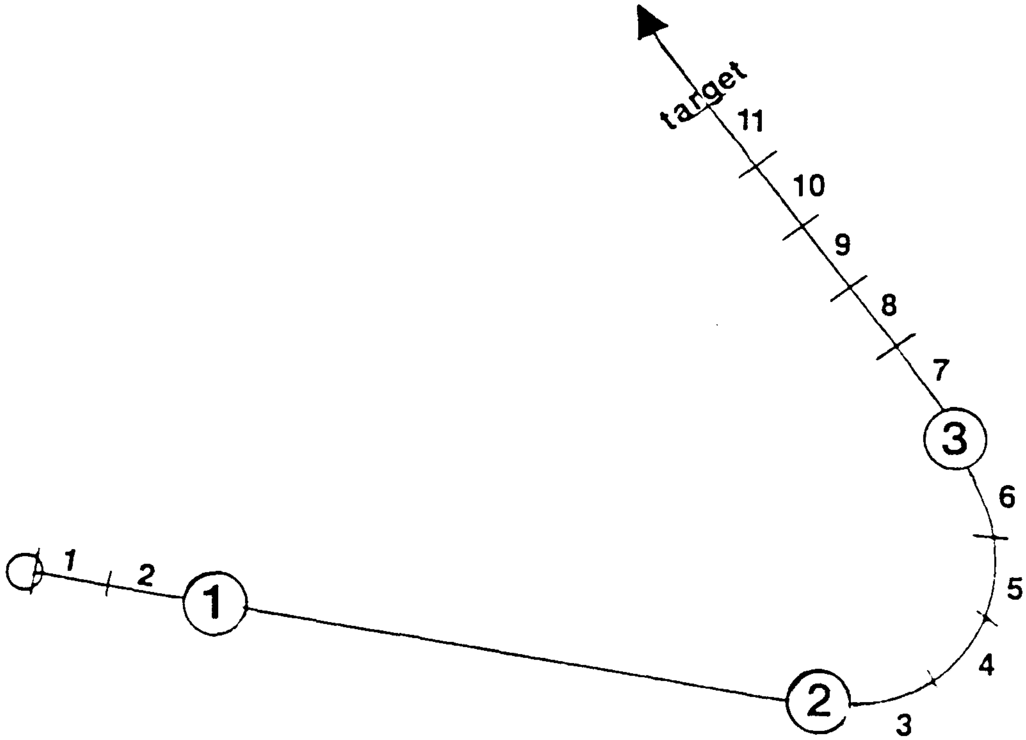


Figure 7

HMD; INGRESS, FLIGHT DELTA

SUBJECT 1; STIMULATION AT 54 Hz

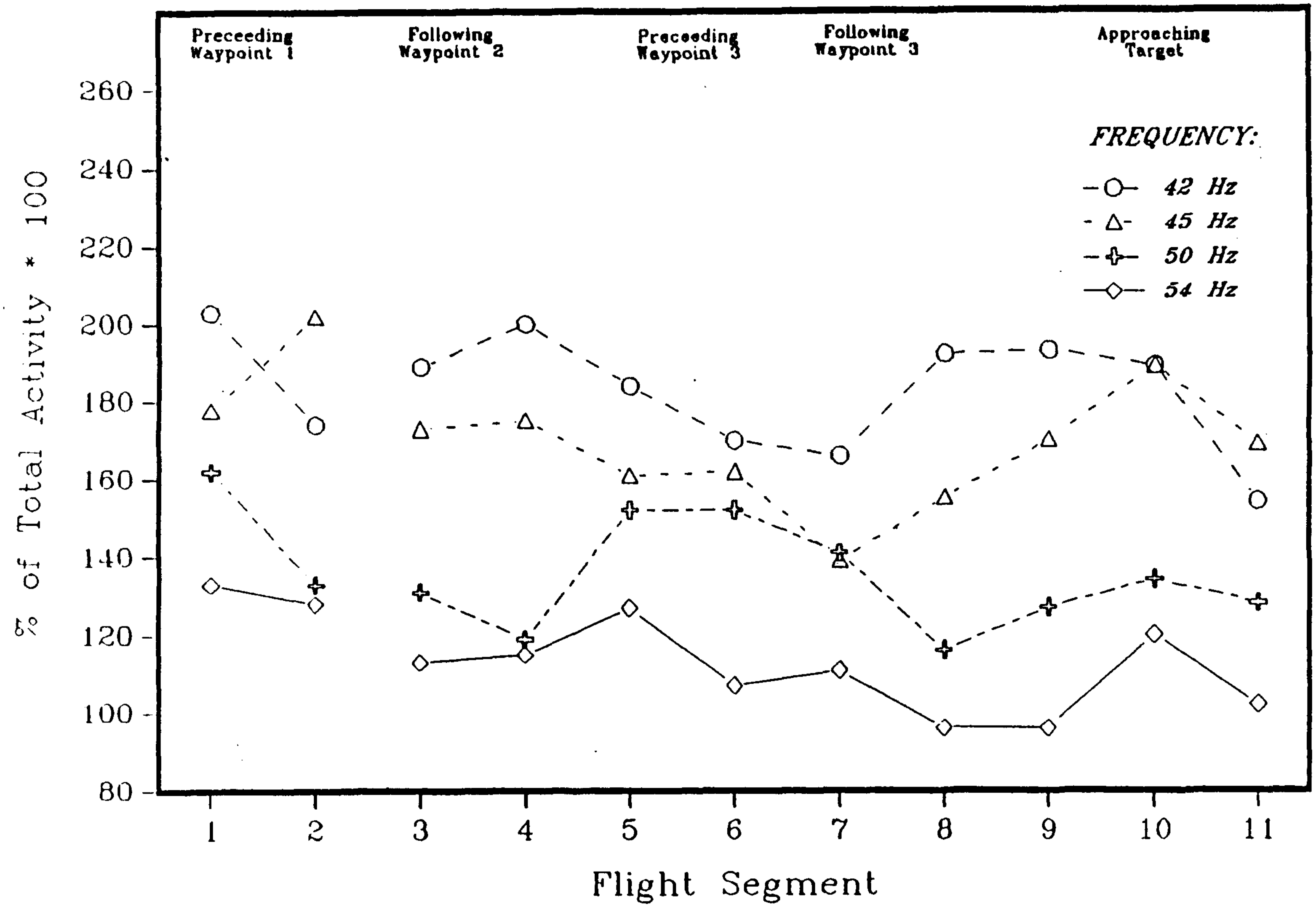


Figure 8

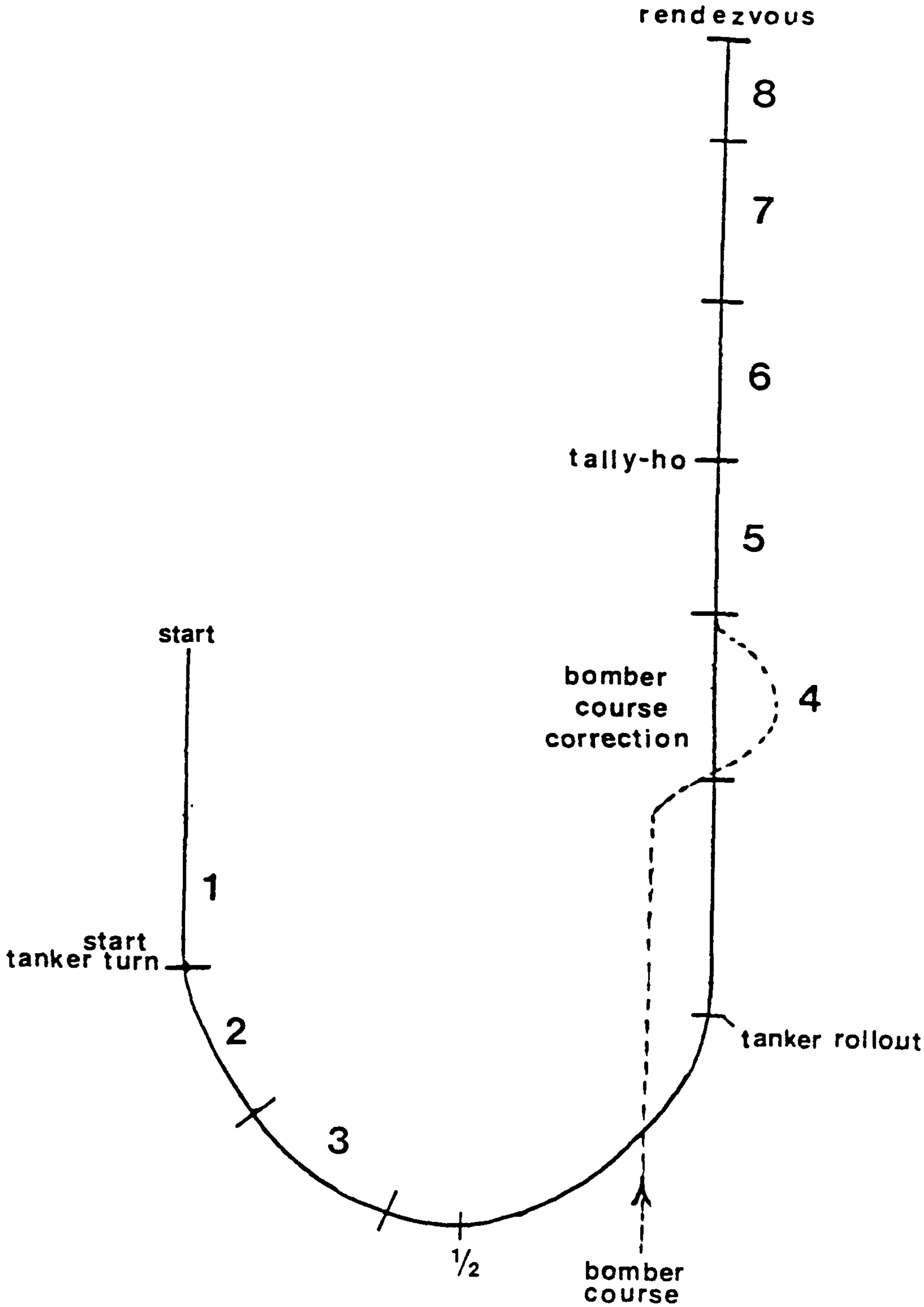

rendezvous
8
7
6
tally-ho
5
start
bomber
course
correction
4
1
start
tanker turn
2
tanker rollout
3
1/2
bomber
course

Figure 9

of flight delta, this took the form of delaying for one mile the rollout of the tanker, which therefore overshot the bomber course. As can be seen in Figure 9, approximately a minute after tanker rollout, the bomber (dotted line) instituted a right course correction, apparently overshot the tanker, made a another correction and brought the bomber on the tanker course. As with the ingress flight, the refuel flight was broken up into segments for analysis. These are indicated along the tanker course in Figure 9 by the numbers 1 to 8.

6.4.2 Within Flight Workload Estimates. In Segment 1, the tanker was proceeding along a straight course, as was the bomber, there was no possibility of the pilot sighting it, and consequently these were judged to be low workload periods. Though the tanker initiated its turn during segments 2 and 3, there was little for the bomber pilot to do but monitor the tanker's course while maintaining his own course, again a relatively low workload condition. Following the tanker rollout, however, the series of course corrections initiated by the bomber pilot probably represents a relatively high workload condition, especially since the initial maneuvers were not very effective. Segment 4 would reflect this. Segments 5 and 6 are straight flight to overtake the tanker; we would rate these periods somewhere between the low workload initial segments and the final segments, 7 and 8, which required somewhat finer adjustments in anticipation of rendezvous. These estimates are summarized in Table 2.

Table 2

Workload Estimates for Segments of Refuel Flight Delta for Subject 1

Workload Estimate	Flight Segment
Low	1,2,3
Medium	5,6
High	4,7,8

The data for the refuel flight are plotted in Figure 10. In addition, Figure 11 contains a plot of the data averaged according to the workload categorization above . Unlike for the ingress flight, there is fair agreement between the estimated workload and depression of activity at 54 Hz. There is no such relationship between estimated load and power for any of the nonstimulated frequencies. Of course, the workload estimates were rather informally arrived at and are subject, therefore, to the variability of such measures. However, they were

HMD; REFUEL, FLIGHT DELTA

SUBJECT 1; STIMULATION AT 54 Hz

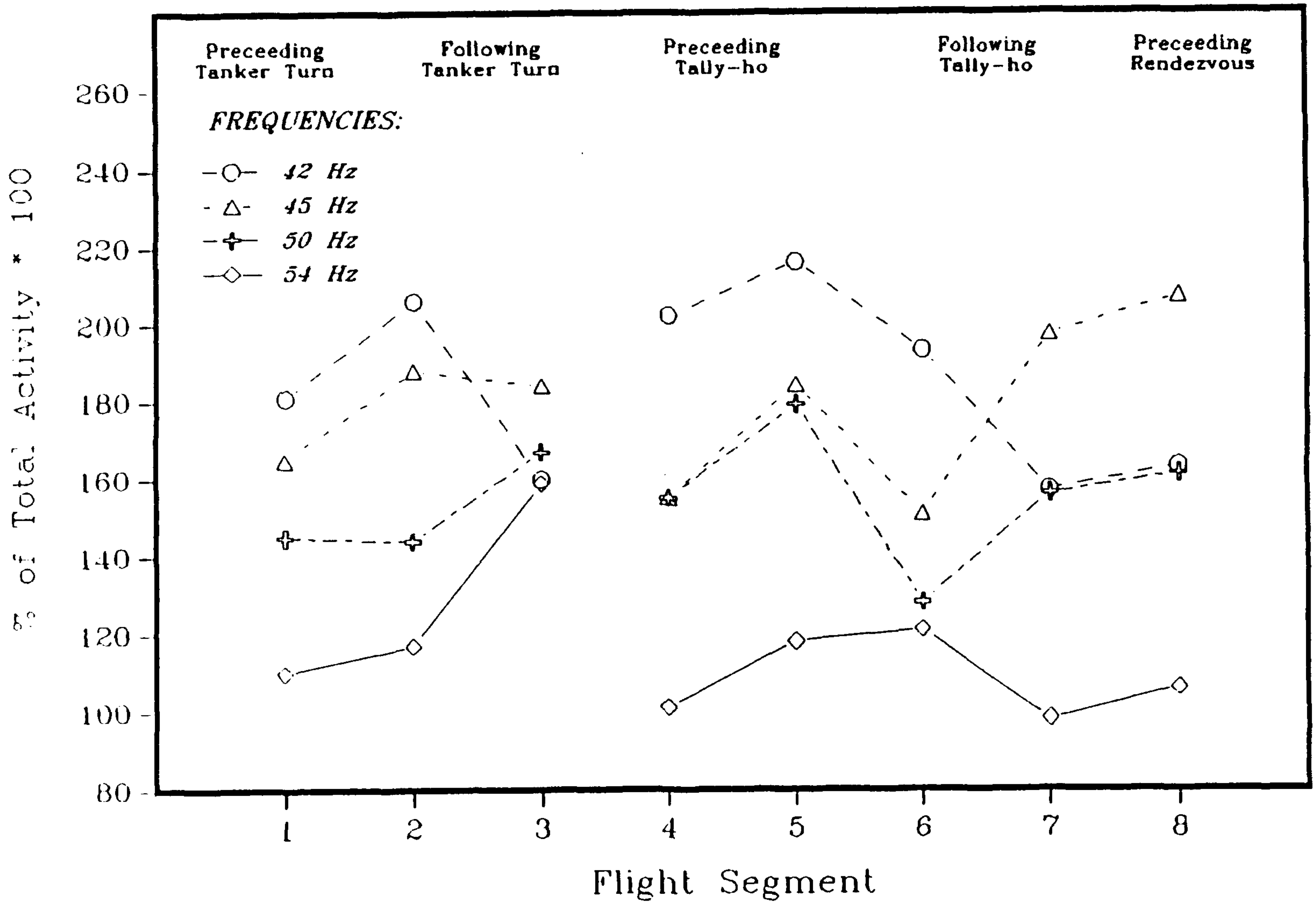


Figure 10

ACTIVITY UNDER THREE LEVELS OF WORKLOAD

SUBJECT 1; HMD: STIMULATION AT 54 Hz; REFUEL; FLIGHT DELTA

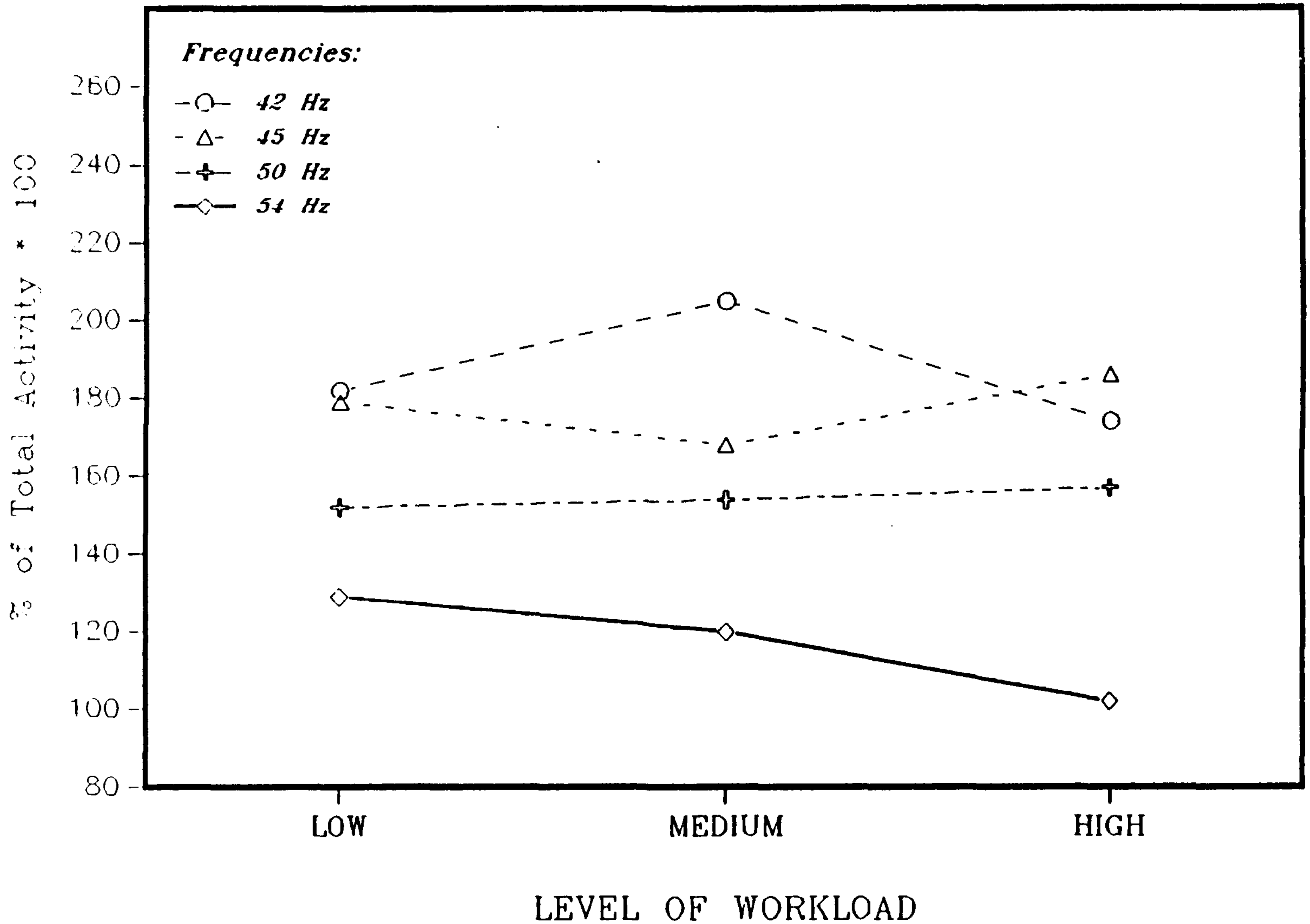


Figure 11

determined by three independent raters whose judgments were almost identical.

6.5 SWAT Ratings. SWAT ratings were taken at the end of each flight, and are summarized in Table 2A. For exploratory purposes, paired comparisons were carried out between relevant conditions. Only one condition stood out: stress, under Ingress-Threat was significantly higher than stress under either Ingress-noThreat or refuel. No comparisons between parallel HMD and NoHMD conditions were statistically significant.

It is our contention that the usefulness of these ratings in the present contex is limited. Whereas the SWAT ratings apply to an entire flight, the measures developed here are designed to reflect workload over brief time periods. Observation of the application of these scales suggested to us that a task punctuated by a brief period of high workload, but otherwise uneventful, will likely yield an invalid measure. We suggest that the point in the flight at which this brief high load period, such as a threat, is introduced, is critical; it is more likely to be reflected in an increased SWAT rating if it is late rather than early in the flight. That is, the closer it is to the time at which the rating is to be given, the greater its effect will be on the rating.

Note also the likelihood that the rating under such conditions will not really characterize the entire flight but will be weighted by this brief event within the flight. It seems to us that SWAT ratings are more applicable in a situation where the workload is relatively uniform throughout. These speculations are amenable to experimental test.

7.0 Conclusions

7.1 Simulator Results. Although prior laboratory work was encouraging in suggesting that steady-state potentials (photic driving) could be established with stimulation frequencies above the flicker fusion threshold, the simulation test of those conclusions cannot be said to have been eminently successful.

Only one of the four pilots for whom we had acceptable EEG records demonstrated what we considered to be evidence of photic driving, and this was assessed under the most ideal circumstances to be found in the simulation setting: eyes-open, looking directly at the flickering HMD. This pilot exhibited an increase in power at 54 Hz when it was the stimulating frequency but no change at 54 Hz when stimulated at one of the other three frequencies.

TABLE 2A

SWAT RATINGS AS A FUNCTION OF THREAT, FLIGHT TYPE, AND USE OF HMD

INGRESS-NO THREAT

	HMD			NoHMD		
S	TIME	EFFORT	STRESS	TIME	EFFORT	STRESS
1	2.0	2.0	2.25	2.0	2.0	2.5
2	1.3	1.67	2.0	1.3	1.25	1.3
3	1.3	2.0	1.0	1.3	2.0	1.0
4	1.0	1.0	1.0	1.5	2.0	1.0
5	1.5	2.0	1.5	1.0	2.0	1.0
M	1.42	1.73	1.55	1.42	1.85	1.36

INGRESS-THREAT

	HMD			NoHMD		
S	TIME	EFFORT	STRESS	TIME	EFFORT	STRESS
1	-	-	-	-	-	-
2	2.0	3.0	3.0	1.0	2.0	1.0
3	2.0	2.0	2.0	2.0	2.0	2.0
4	1.0	1.5	2.0	2.0	2.0	2.0
5	2.0	2.5	2.0	2.0	2.0	1.0
M	1.75	2.25	2.25	1.75	2.0	1.5

REFUEL

	HMD			NoHMD		
S	TIME	EFFORT	STRESS	TIME	EFFORT	STRESS
1	1.0	1.5	2.0	1.5	2.0	2.25
2	1.0	1.5	1.5	1.0	2.0	2.0
3	1.0	2.0	1.0	1.5	2.0	1.0
4	1.5	2.0	1.25	1.3	2.0	1.7
5	1.0	2.0	1.5	1.0	2.0	1.5
M	1.1	1.8	1.45	1.26	2.0	1.69

AVERAGE OF ALL CONDITIONS

HMD			NoHMD		
TIME	EFFORT	STRESS	TIME	EFFORT	STRESS
1.42	1.93	1.75	1.48	1.95	1.52

Although no definitive statement can be made concerning why other subjects did not exhibit evidence of driving, there are many factors that could be pointed to as potentially significant contributors. Preliminary work clearly demonstrated substantial individual differences in optimal frequency for photic driving. In the simulation procedure, there was no time available to ascertain this value for any pilot; the stimulating frequencies were selected in a manner that could have missed the optimal for a given pilot.

A second potential source of the difficulty in demonstrating photic driving more effectively is the low intensity of the HMD. As indicated at the outset of the EEG section, the intensity was informally set by the pilot to his maximum comfort level and not calibratable. While the system was capable of higher intensities, the pilots preferred the dimmer displays. Yet another problem, along these same lines, is the power output at the stimulating frequency, which ranged from as little as 33% to a maximum of 74% of total power; most commonly, the output was in the low 50s. Thus, the intensity, low in the first place, was further attenuated, both factors reducing the probability of the driving response.

Another possibility was that pilots may have interpreted scintillation of the display, which is a property of the system, as flicker, with a consequent higher estimated flicker fusion level. This would increase the frequencies of the flicker used and thus also tend to reduce driving.

Finally, only enough time was available to run two baseline eyes-open/eyes-closed tests for each set of four flights, one at the beginning and one at the end of each HMD set. This did not insure a high degree of reliability of these measures. As mentioned earlier, a more optimal procedure would have been to run a series of eyes-open/-eyes-closed trials before and after each flight at the frequency of stimulation of that flight.

We would like to add to the above discussion, that the factors mentioned are speculative. It is quite possible that photic driving is simply not demonstrable in the great majority of subjects under these conditions. Nevertheless, in the absence of control over these potentially significant variables, we cannot determine which conclusion is correct.

We will turn now to the workload/driving relationship within the ingress and refuel flights. With respect to ingress, the data do not offer any evidence for any relationship. The only flight data that seem to support the hypothesis that driving reflects workload comes from the refuel flight. It is not possible, however, to evaluate the magnitude of the workload/driving relationship that was observed in that flight. Though they appear to agree well, that is, increases in estimated workload are accompanied by average decreases in the EEG response to the flicker, the individual values contributing to this average do not sustain this view. Thus, we see in Figure 10 that variation among the first three 54 Hz points, which comprise the estimated low workload subtask, is greater than the variation in percent activity across workload levels as seen in Figure 11. It is tempting, of course, to speculate that the beginning of the flight (points 1 and 2) represents a slightly higher load than later (point 3), but without objective evidence to back up this ad hoc speculation, it would not be profitable to argue the point.

7.2 Overall Evaluation of EEG Effort. Despite the weakness of the evidence for a workload effect, several points have been established by this work. First, a reasonable EEG can be recorded in the simulation setting, a fact not altogether apparent at the outset of this research. The anticipated coupling artifact, induced electrically (i.e., nonphysiologically) by the flickering stimulus in earlier trials, appeared to have been controlled. Second, flickering the HMD can be accomplished without the subject's awareness, and result in interpretable EEG output. Third, the percent of total activity seems to be a sensitive measure of the following response of the brain to flickering light, and is essentially redundant with the log measure and without some negative features of the latter. Finally, there seemed to be a pattern in one subject that was consistent with a driving effect, and also, if one compares the driving under different conditions (Figure 6), evidence of a workload effect. However, the latter, while demonstrable on average, was not reliable in each replication.

It is clear to us that this area needs more controlled laboratory research before the feasibility of its application can be adequately tested. The following section will be devoted to outlining such research.

7.3 Projection for Future Research

7.3.1 As is apparent, the choice of stimulating frequency for a given subject is a critical one. Not only are there differences among individuals in the frequency that optimally produces photic driving, but there is reason to believe that intensity is a significant variable in determining this level. It was shown earlier in this report that intensity reduction decreased driving at a frequency chosen to be optimal. What had not been ascertained, however, was whether at the lower intensity the optimal frequency had changed.

Several lines of evidence suggest that intensity does have a bearing on the optimal frequency for driving. One piece of evidence for this inference comes from the classical literature (Hecht & Shlaer, 1936), viz., that critical flicker frequency (cff), the frequency at which a flickering stimulus is perceived as steady, increases as a function of intensity. Second, Simonson & Blankstein, (1961) found that optimal driving frequency as well as cff increase as a function of age. We believe that these reflect the declining capacity of the aging nervous system to resolve rapidly occurring stimuli, and therefore, that these correlated age effects are both manifestations of the same mechanism. It follows from this and the cff/intensity relation that intensity will affect optimal driving frequency as it does cff. Note that this model is in conflict with the view implicit in Wilson and O'Donnell's (1986) report. In their work, the cognitive significance of driving in various frequency ranges was treated as if these frequencies were constant for each subject, analogous to "resonant" frequencies that reflect activity in distinct cognitive systems. The argument presented here suggests that these frequencies vary with stimulus parameters although there may still be non-overlapping systems subserving distinct functions.

This inference may be tested by flickering subjects at a variety of frequencies each presented in combination with a series of intensities. Each frequency/intensity combination would be repeated many times. Spectral analyses would be performed and the power output in 1 Hz bins would be calculated. In all cases, the stimulus would be a pure sine wave, which produces greater (% total) power than a square wave. In this manner, it could be determined whether optimal frequency shifts as intensity changes.

7.3.2 Following the above investigation, it would be essential to determine whether workload affects the driving response. The simulator is not the ideal environment to demonstrate this phenomenon. Several of the potentially confounding variables have already been discussed, and we may add variation in the subject's direction of gaze during the period in which an EEG sample is to be taken for spectral analysis. Thus, if the subject shifts his gaze during such a period, so that the stimulus falls on the peripheral retina, our data show that this will reduce output at the stimulating frequency. To compound matters, one can conceive of a correlation between such behavior and degree of workload. That is, under just those conditions where the workload demands are increasing, the pilot may feel it necessary to scan the environment to acquire information not available on the HMD. This would have the effect of reducing the driving response and artifactually support the hypothesis. It is obvious that this will remain a problem to be addressed in subsequent research. This study, however, will concentrate on demonstrating the driving/workload relationship under ideal conditions; factors that may interfere with the relationship and effective means of compensating for them will be deferred to a later date.

Subjects will be given tasks that differ in workload. The tasks will be designed so that each is relatively uniform in workload throughout its course, or at least that there are sufficiently long periods within a task that are at a specifiable and constant workload to permit repeated EEG sampling at that level. The task will be designed so that the attention to the flickering visual stimuli is necessary in order to carry out the task. An example of such a task is that used by Vicente, Thornton, and Moray (1987), in which the subject guided a computer-simulated "hovercraft" down a winding river. To manipulate workload, they varied both the width of the river and the standard deviation of the turbulence distribution added to the joystick output. For present purposes, the rectangle of light (the hovercraft) on the computer terminal would be flickered. This task would meet the criterion of insuring that the subject is attending to the flickering stimulus.

7.3.3 Another direction that this project might take concerns the changing nature of the task. At various points during a flight, the character of the task may differ considerably. At one point, the pilot may be carefully guiding his craft through a series of difficult maneuvers. At another, he may be absorbing information presented to him either visually or by audio communication. At yet another phase of the flight, the pilot may be integrating information and considering what the best course of action would be. These activities may represent <u>qualitatively</u> different workloads for the pilot.

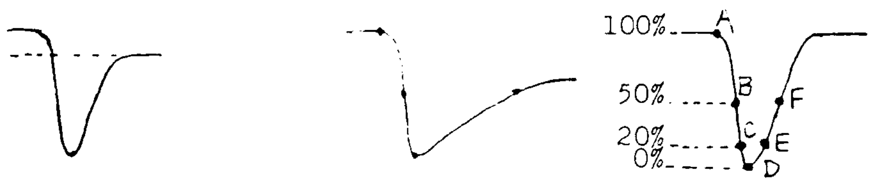
The question for us is whether this measure of workload, suppression of photic driving, is equally sensitive to these essentially different tasks: Does it simply represent a general measure of attention without regard to the nature of the task? Or, does the quality of the task play a vital role in the activity of the population of neurones detected by our recording electrode(s)? Data supporting the latter have been reported by Wilson (1981). If this proves to be the case, it would suggest the use of multiple recording sites to assess the component processes drawn on by a particular task. This assumes, of course, that there exist cortical sites whose activity differentially reflect distinct task dimensions.

C. SACCADE AND BLINK ANALYSIS

1.0 Measurement of Blinks and Vertical Saccades

Saccade and blink detection algorithms were used for this analysis. Since current display routines allow us to view only two channels of data concurrently, the analysis was a two-step procedure. We first analyzed blinks and horizontal saccades to allow us to evaluate each of these parameters independently and to abstract information about the co-occurence of blinks and horizontal saccades. The second analysis involved blinks and vertical saccades. We were concerned here as well with the temporal relationship between blinks and vertical saccades.

One problem encountered in the analysis of blink data was the occurrence of many blinks in coordination with vertical eye movements. Since one cannot identify vertical saccades made during a blink with the use of the electrooculographic (or any other) procedures, the occurrence of such saccades had to be inferred. Accordingly, a saccade was presumed to have occurred if the vertical position of the eye following the blink was not the same as it was at blink initiation. For example, in Figure 12A the voltage level at termination of the blink (and saccade) is below the voltage at onset. This indicates that the eye position at termination was higher than it was at blink initiation. We have not, as yet, developed a computer algorithm to make this assessment; it was made using manual editing routines.



A B C

Figure 12

Our blink identification algorithm requires that the voltage following the trough of a deflection return to a level at least half the distance between blink initiation and maximum lid closure. If it does not do so in a specified time (200 msec in the present analysis), the pattern is not accepted as a blink. Our analysis, thus, underestimates the frequency of blink occurrence.

A second problem observed in the present data set, and one seldom encountered by us, was a combination of eye movements that could be interpreted (by our algorithm) as a blink. For example, an upward saccade followed by a downward glissade (slower eye movement) that returned the eye somewhat more than half the distance of the initiating saccade, (see Figure 12B) would be interpreted as a blink by the algorithm. These eye movements could be discriminated from true blinks on the basis of the difference in the form of the final voltage deflections: the glissade terminating the blink is sharper than the glissade portion of the saccade (compare A and B, Figure 12). These pseudoblinks (i.e., they were identified as blinks by the computer program) were manually edited from the data.

We are somewhat puzzled by the glissade portion of the eye movement. Though these eye movements appear similar to those that compensate for head movements in the vertical plane, we assured ourselves that they were not such compensatory eye movements by relating them to the head movement data and finding no consistent relationship.

1.1 Data Output; Hard Copy

1.1.1 Blinks. Table 3 depicts "raw" outputs from these analyses, which contain information about each blink and saccade. Column 1 identifies the time of occurrence of either a blink or saccade. Columns 2 through 7 present information about blinks that were initiated at the time specified in column 1. (For the letters in the following explanations, refer to Figure 12C.) Column 2 identifies the time between successive blinks, and column 3, blink amplitude (D minus A, in A/D units, proportional to voltage). Column 4 ("half duration") contains the time between the point where a blink achieves half of its total amplitude, and the point, in the reopening phase, at which it recrosses that same (voltage) level (F minus B). "Window duration" (column 5) is similar to the half duration measure except that it is for an optional percentage specified by the operator. That window, labeled "user-set window" in the table heading, was 20 percent (i.e., 20% up from full closure) in this analysis (E minus C). Column 6, "descent (50%)", is the time from half closure to full blink closure (D minus B), while column 7, "closing duration", refers to the time between blink initiation and full closure (D minus A).

1.1.2 Saccades. Columns labeled from A-E in Table 3 deal with saccade information. Column A refers to the time between successive saccades. Column B refers to saccade duration, i.e., the time between saccade initiation and termination. Column C, labeled "drift," refers to voltage level shifts between successive saccades, i.e., the change in position of the eye from the termination of one saccade to the initiation of the next one. Such shifts may reflect the occurrence of slow pursuit movements between

TABLE 3A

COMBINED BLINK AND SACCADE DATA FOR FILE: DK1:5ANA2H.DAT

Coincidence of vertical + horizontal saccades

BLINK AMPLITUDE CRITERION: 200 A/D UNITS
BLINK MAXIMUM DURATION: 200 MSECS
BLINK DROP CRITERION: 100 A/D UNITS
USER-SET WINDOW: 20 PERCENT

SACCADE MINIMUM AMPLITUDE CRITERION: 150 A/D UNITS
SACCADE BIG INCREASE/DECREASE CRITERION: 150 A/D UNITS
SACCADE WINDOW CRITERION: 200 A/D UNITS
SAMPLING RATE: 1 POINT PER 10 MSECS

			BLINKS						SACCADES				
		1	2	3	4	5	6	7	A	B	C	D	E
		TIME (SEC.)	INTERVAL (SEC.)	AMPLITUDE (A/D UNITS)	HALF DUR.	WINDOW DURATION	DESCENT(50%) (SEC.)	CLOSING DURATION	FIXATION (SEC.)	DURATION (SEC.)	DRIFT A/D UNITS	AMPLITUDE A/D UNITS	PEAK VELOCITY A/D UNITS
30	1	0.560	******	1104.	0.150	0.090	0.070	0.120					
	1	• 0.590							******	0.130	******	-325.	50.
	2	• 3.400							2.680	0.090	-22.	275.	-68.
20	2	4.350	3.790	816.	0.120	0.070	0.050	0.070					
	3	4.370							0.880	0.190	232.	-738.	72.
20	3	5.750	1.400	1038.	0.170	0.070	0.050	0.070					
	4	• 5.770							1.210	0.110	91.	308.	-65.
	4	6.550	0.800	734.	0.110	0.060	0.040	0.050					
	5	7.190							1.310	0.050	99.	176.	-66.
10	6	8.080							0.830	0.120	79.	-777.	114.
	6	8.090	0.980	738.	0.090	0.060	0.030	0.060					
	7	9.000							0.800	0.130	209.	745.	-101.
10	7	10.940	2.850	1196.	0.140	0.070	0.040	0.080					
	8	10.950							1.820	0.100	-41.	-403.	76.
	9	12.270							1.220	0.050	-46.	168.	-64.
10	8	12.830	1.890	664.	0.070	0.040	0.040	0.070					
	10	• 12.840							0.520	0.160	-36.	304.	-59.
	9	14.290	1.460	1295.	0.140	0.070	0.060	0.120					
	11	• 14.300							1.300	0.150	-27.	-339.	55.
	12	• 15.760							1.310	0.080	161.	183.	-51.
10	10	17.050	2.760	1378.	0.140	0.080	0.060	0.110					
	13	• 17.060							1.220	0.150	7.	-307.	57.
30	11	18.240	1.190	548.	0.080	0.050	0.040	0.080					
	14	• 18.270							1.060	0.110	22.	297.	-84.
	12	22.290	4.050	855.	0.100	0.050	0.030	0.070					
	15	23.080							4.700	0.050	-130.	208.	-96.
20	16	• 23.590							0.450	0.100	46.	-817.	113.
	13	23.610	1.320	438.	0.090	0.050	0.030	0.060					
20	14	24.320	0.710	695.	0.080	0.050	0.040	0.070					
	17	• 24.340							0.650	0.130	111.	736.	-123.
50	15	25.020	0.700	622.	0.110	0.050	0.040	0.120					
	18	• 25.070							0.600	0.120	-52.	-696.	87.
	19	• 30.950							5.760	0.200	253.	670.	-74.
20	16	31.710	6.690	394.	0.070	0.040	0.040	0.050					
	20	• 31.730							0.590	0.090	-366.	243.	-57.
10	17	33.920	2.210	1075.	0.090	0.050	0.030	0.070					
	21	• 33.930							2.110	0.140	-33.	-295.	44.
30	18	35 270	1.350	263.	0.060	0.040	0.030	0.090					
	22	• 35.300							1.230	0.090	-42.	397.	-70.

TABLE 3B

10	23 • 37.260							1.870	0.120	-25.	-751.	145.
	19 37.270	2.000	482.	0.100	0.060	0.040	0.090					
10	20 38.490	1.220	679.	0.090	0.060	0.040	0.070					
	24 38.500							1.120	0.130	92.	732.	-106.
	25 39.770							1.140	0.110	-128.	-326.	69.
10	21 40.350	1.860	307.	0.080	0.060	0.050	0.070					
	26 • 40.360							0.480	0.070	-23.	243.	-80.
20	22 41.610	1.860	1244.	0.150	0.060	0.050	0.110					
	27 • 41.630							1.200	0.120	177.	-317.	51.
	28 42.490							0.730	0.080	94.	332.	56.
10	23 42.640	1.030	646.	0.90	0.060	0.050	0.070					
	29 42.650							0.080	0.140	56.	423.	-72.
	30 43.290							0.500	0.060	-190.	175.	-84.
20	31 44.170							0.820	0.100	97.	-719.	119.
	24 44.190	1.550	530.	0.070	0.040	0.040	0.080					
70	25 45.010	0.820	1272.	0.120	0.070	0.050	0.090					
	32 45.090							0.810	0.080	273.	286.	-57.
	33 45.600							0.440	0.090	-29.	184.	-74.
10	26 46.700	1.690	1177.	0.140	0.080	0.050	0.100					
	34 • 46.710							1.020	0.110	112.	-467.	75.
30	27 47.500	0.800	592.	0.070	0.040	0.030	0.070					
	35 • 47.530							0.710	0.130	143.	290.	-73.
0	36 • 48.390							0.730	0.160	70.	-738.	94.
	28 48.390	0.890	488.	0.090	0.050	0.050	0.080					
	29 49.800	1.410	598.	0.100	0.050	0.030	0.070					
	37 • 53.580							5.030	0.090	147.	376.	-71.
	38 54.680							1.010	0.060	117.	-224.	69.
40	30 54.880	5.080	541.	0.070	0.040	0.030	0.090					
	39 • 54.920							0.180	0.120	60.	-497.	111.
	40 • 56.140							1.100	0.210	111.	590.	-76.
0	41 56.830							0.480	0.210	-326.	397.	-75.
	31 56.830	1.950	205.	0.050	0.040	0.020	0.060					
	42 58.840							1.800	0.030	-255.	165.	-104.
	32 60.980	4.150	1184.	0.150	0.080	0.050	0.080					
	43 61.030							2.160	0.090	-106.	-339.	83.
	44 62.040							0.920	0.030	-14.	193.	-74.
	45 62.870							0.800	0.070	-13.	-194.	48.
	46 • 63.360							0.420	0.070	-24.	272.	-59.
	47 • 63.820							0.390	0.070	-272.	220.	-79.
30	33. 66.920	5.940	406.	0.070	0.040	0.040	0.070					
	48 • 66.950							3.060	0.070	-163.	287.	-78.
	49 • 70.300							3.280	0.040	-219.	159.	-76.
10	34 71.350	4.430	442.	0.080	0.050	0.040	0.090					
	50 • 71.360							1.020	0.130	-151.	171.	-38.
	35 73.500	2.150	1363.	0.190	0.090	0.070	0.110					
10	36 74.230	0.730	369.	0.070	0.050	0.040	0.070					
	51 • 74.240							2.750	0.090	-230.	190.	-63.
	37 76.080	1.850	1217.	0.170	0.080	0.060	0.090					
10	38 76.740	0.660	394.	0.070	0.040	0.040	0.060					
	52 • 76.750							2.420	0.090	-264.	227.	-43.

TABLE 3C

53 •	77.610							0.770	0.100	-70.	329.	-58.
20 39	78.140	1.400	48.	0.090	0.050	0.050	0.080					
54 •	78.160							0.450	0.120	-148.	-342.	59.
55 •	79.160							0.880	0.080	222.	-190.	66.
56 •	79.860							0.620	0.060	16.	159.	-66.
40	81.540	3.400	987.	0.110	0.050	0.040	0.070					
20 41	82.310	0.770	741.	0.070	0.050	0.040	0.070					
57 •	82.330							2.410	0.080	-94.	225.	58.
42	83.850	1.540	694.	0.070	0.050	0.030	0.060					
58 •	84.390							1.980	0.050	-109.	-163.	65.
43	84.500	0.650	375.	0.100	0.050	0.040	0.120					
44	85.360	0.860	483.	0.140	0.060	0.030	0.050					
10 45	85.870	0.510	1000.	0.080	0.040	0.040	0.070					
59	85.880							1.440	0.080	-73.	434.	-101.
40 46	86.330	0.460	552.	0.070	0.040	0.040	0.070					
60 •	86.370							0.410	0.080	-242.	-287.	73.
61 •	87.680							1.230	0.050	244.	215.	-59.
0 47	87.680	1.350	1097.	0.150	0.040	0.050	0.070					
48	88.060	0.400	797.	0.130	0.090	0.050	0.060					
53 •	88.110							0.380	0.100	-78.	-316.	60.
49	88.670	1.590	791.	0.090	0.060	0.030	0.050					

34 BLINKS COINCIDENT WITH HORIZONTAL SACCADES

SACCADE DURATION	N	$\bar{X}$	σ	
SACCADES ASSOCIATED W/BLINKS	27	82.6	42.57	t = 3.468
SACCADES WITHOUT BLINKS	35	117.1	33.34	

31 Blink Saccade cooccurrence, i.e., 30 msec delay or less

4 Blink Saccade non-occurrence, i.e., 40 msec delay or longer

saccades, or may be produced by artifacts, such as skin potential shifts. Column D refers to the amplitude of the saccade, and column E, "peak velocity," refers to the largest change (in A/D units) occurring during a saccade. In the present instance, it is the largest shift occurring between 10 msec samples during the saccade (since sampling period is 10 msec). The criterion used for defining a saccade was considerably more liberal than our usual definition of a saccade. Thus, both relatively rapid pursuit and compensatory eye movements were accepted as saccades in this analysis.

1.2 Interpreting Data Output

In Table 3, we see that a blink occurred 560 msec into this digitization run, and that 30 msec later, a horizontal saccade was initiated. Since the closing duration of the blink was 120 msec (column 7), and the saccade duration 130 msec, the saccade terminated 40 msec after the eyelid started to reopen. In the table, we have manually identified blinks that occurred concurrently with a saccade. Concurrence is defined as a time lag between blink and saccade initiation of 80 msec or less. In fact, the great majority of blink-saccade latencies fell in the ± 30 msec range.

The column on the left, between that containing the numbered blinks and saccades, and the one identifying the time of occurrence of the numbered events, was manually added. This column deals with oblique saccades, which appear in the record as simultaneous horizontal and vertical saccades. This information was abstracted by combining the horizontal and vertical saccade analysis. If a saccade in either plane was initiated within 60 msec of that in the other plane, the two saccades were considered to be coincident. As is apparent in Table 3, not only does the first blink occur concurrently with a saccade in the horizontal plane, there is a concurrent saccade in the vertical plane (i.e., eye position in the vertical plane following the blink is markedly different from eye position preceding the blink).

1.3 Blink and Saccade Data Summaries. Table 4 summarizes information about the blinks abstracted in Table 3 and is self-explanatory. Table 5 requires some clarification: saccade data are broken down into 25 columns and three levels. Referring to the third section on saccade amplitude, the first row breaks amplitude into 20 A/D unit steps. Thus, row 1/column 1 includes all amplitudes from 0-19 msec, row 1/column 2, 20-39 msec, etc. There are no entries for the first seven columns, because our criterion for defining saccade amplitude (see upper right-hand corner of Table 3) did not allow for the identification

TABLE 4

BLINK SUMMARY

AMPLITUDE		HALF DURATION		WINDOW DURATION		DESCENT (50%)		CLOSING DURATION	
A/D UNITS	FREQ	MSECS	FREQ	MSECS	FREQ	MSECS	FREQ	MSECS	FREQ
200- 219	1	1- 10	0	1- 10	0	1- 10	0	1- 10	0
220- 239	0	11- 20	0	11- 20	0	11- 20	1	11- 20	0
240- 259	0	21- 30	0	21- 30	0	21- 30	11	21- 30	0
260- 279	1	31- 40	0	31- 40	11	31- 40	20	31- 40	0
280- 299	0	41- 50	1	41- 50	14	41- 50	11	41- 50	2
300- 319	1	51- 60	1	51- 60	10	51- 60	4	51- 60	7
320- 339	0	61- 70	11	61- 70	6	61- 70	2	61- 70	18
340- 359	0	71- 80	6	71- 80	5	71- 80	0	71- 80	9
360- 379	1	81- 90	8	81- 90	3	81- 90	0	81- 90	5
380- 399	3	91-100	4	91-100	0	91-100	0	91-100	1
400- 419	1	101-110	3	101-110	0	101-110	0	101-110	3
420- 439	1	111-120	2	111-120	0	111-120	0	111-120	4
440- 459	2	121-130	1	121-130	0	121-130	0	121-130	0
460- 479	0	131-140	5	131-140	0	131-140	0	131-140	0
480- 499	3	141-150	4	141-150	0	141-150	0	141-150	0
500- 519	0	151-160	0	151-160	0	151-160	0	151-160	0
520- 539	1	161-170	2	161-170	0	161-170	0	161-170	0
540- 559	3	171-180	0	171-180	0	171-180	0	171-180	0
560- 579	0	181-190	1	181-190	0	181-190	0	181-190	0
580- 599	2	191-200	0	191-200	0	191-200	0	191-200	0
OVER 599	29	OVER 200	0	OVER 200	0	OVER 200	0	OVER 200	0

	AMPLITUDE	HALF DURATION	WINDOW DURATION	DESCENT (50%)	CLOSING DURATION
MEAN	748.08	102.24	57.76	42.45	78.78
VARIANCE	105836.59	1142.77	226.11	118.88	340.14
ST. DEV.	325.33	33.80	15.04	10.90	18.44
MEDIAN	679.00	90.00	50.00	40.00	70.00

NOTE: MEDIAN CALCULATED FROM RAW SCORES, NOT FROM FREQUENCY DISTRIBUTION.

49 BLINKS

TABLE 5

SACCADE SUMMARY

FIXATION DURATION:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
20 MS. STEPS:	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	1	1	2	1	52
100 MS. STEPS:	1	1	0	2	7	3	3	4	7	1	4	3	6	3	1	0	0	0	3	1	0	2	0	0	9
500 MS. STEPS:	11	18	17	4	4	2	2	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

SACCADE DURATION:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
10 MS. STEPS:	0	0	0	2	1	4	4	5	6	9	5	4	6	6	2	2	2	0	0	1	1	2	0	0	0
20 MS. STEPS:	0	2	5	9	15	9	12	4	2	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100 MS. STEPS:	31	28	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

SACCADE AMPLITUDE:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
20 A/D STEPS:	0	0	0	0	0	0	0	2	6	6	2	4	2	2	6	5	6	1	1	2	1	2	0	1	13
50 A/D STEPS:	0	0	0	14	8	8	12	3	3	2	0	1	0	2	6	2	1	0	0	0	0	0	0	0	0
100 A/D STEPS:	0	14	16	15	5	1	2	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

SACCADE VELOCITY:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
2 A/D STEPS:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	58
5 A/D STEPS:	0	0	0	0	0	0	0	1	2	1	3	11	3	8	9	7	4	1	1	1	3	1	3	1	2
10 A/D STEPS:	0	0	0	1	3	14	11	16	5	2	4	4	1	0	1	0	0	0	0	0	0	0	0	0	0

The correlation coefficient for peak velocity vs. amplitude is 0.655.
The slope of the regression line is 6.01, and the y-intercept is -83.75.

	peak velocity	amplitude
mean:	74.403	363.774
variance:	460.277	38768.016
standard deviation:	21.454	196.898
standard error of estimate:	16.204	148.713

The correlation coefficient for saccade duration vs. saccade amplitude is 0.585.
The slope of the regression line is 2.80, and the y-intercept is 77.76.

	duration	amplitude
mean:	102.097	363.774
variance:	1692.253	38468.016
standard deviation:	41.137	196.898
standard error of estimate:	33.355	159.649

of saccades smaller than 150 A/D units. One finds, for example, that there are 2 + 6 + 6 = 14 saccades smaller than 200 A/D units. The next row breaks saccade amplitude into 50 msec units, again with 14 units following between 150 and 200 msec. The third row breaks the data down into 100 A/D unit steps, and we see that 14 saccades are between 100 and 200 A/D units in amplitude. Since saccade amplitude and duration, as well as amplitude and peak velocity, are (under laboratory circumstances) highly correlated, these individual descriptors of saccade components are not easily interpreted.

Because of these relationships, we have also calculated the linear regression of saccade amplitude on velocity, as well as saccade amplitude on duration.

2.0 Blinks and Saccades in Simulated Flight

2.1 Ingress mission

A typical ingress mission flight plan is presented in Figure 7. There were variations on this theme but the basic structure of the flights was the same. Waypoints are indicated by circled numbers.

Two sets of data were evaluated for the ingress mission. The first dealt with oculometric measures collected around the waypoints. For this analysis, data from the 60 second period prior to arrival at a waypoint, and the 60 second period following crossing of the waypoint were analyzed. We occasionally found that the time between the first and second waypoint was less than 120 seconds. Where this occurred, data around the first and third waypoints were analyzed.

The second segment analyzed dealt with an announced threat, which always occurred following the turn at waypoint two but prior to crossing waypoint three. After a short delay, the threat was declared terminated. In both cases, the 60 second period immediately following the announcement was analyzed.

2.2 Refuel mission

Up to six segments of 60-sec chunks of data were abstracted. These were coded as listed for clarity of presentation; however, the numbers in parentheses refer to the segments in Figure 9.

BT (1) - 60 s period prior to the announcement that the tanker had started his turn.
TT (2,3) - 60 s period after the tanker initiated his turn.
PH (4,5) - 60 s period before the pilot announced sighting the tanker (Tally-ho).
HO (6,7) - 60 s period immediately following the

sighting of the tanker.
RZ (7+,8) - 60 s period preceding rendezvous of the two aircraft.

Where no RZ data are identified, it occurred within 90 seconds or less following HO, or no rendezvous was made.

3.0 Summary of Results

3.1 Blink and Saccade Frequency.

Absolute number of blinks and saccades were expressed as rate measures, events/minute, for all data analyzed for subjects 1 and 5, and are depicted in Tables 6 and 7. Results are as follows:

1. For Subject 1, no consistent differences in blink rate were found between HMD and noHMD conditions (HMD > noHMD in only 4 of 12 segments). Subject 5 blinked consistently more under the noHMD condition (16 out of 16 segments of data analyzed).

2. Both subjects made more horizontal and vertical saccades (estimated at greater than 2°) in the noHMD than in the HMD condition (in all four missions evaluated).

3. Subject 5, for whom data for Threat avoidance and a post-Threat period (return to course) are available, demonstrates:
a) a marked increase in horizontal saccades under the Threat condition, with maintenance of this effect through the Post-Threat period. This effect is seen for both the HMD and NoHMD conditions.
b) For both Threat and Post-Threat conditions, the vertical saccade pattern is the reverse of the horizontal pattern: the HMD condition produced more gaze shifts than the noHMD condition.

3.2 Blink/Saccade Concurrence.

The last column in Tables 6 and 7, labeled "V SAC W/BLINK", needs additional qualification. This designation refers to the concurrence of a blink with a vertical saccade. In the waveform suggesting this occurrence, the eye position (voltage level) following a blink is markedly different from that preceding the blink. A voltage level lower following the blink than preceding it, indicates that the gaze has shifted upward (and vice versa).

These data were abstracted for two reasons. Of major importance was that our algorithm for blink identification, as mentioned earlier, will not identify a blink as such if eye position following a blink returns to a voltage level less than half the total blink amplitude (cf., point F, Figure 12c). Thus, blinks for which gaze direction went up during the course of the blink, would not be computer-identified as blinks. Blinks associated

Table 6

Subject 1, B Mission

	EVENTS/MIN HMD				EVENTS/MIN NOHMD			
	BLINKS	SAC H	SAC V	V SAC W/BLINK	BLINKS	SAC H	SAC V	V SAC W/BLINK
1W	27	35	23	1.5	24.5	67.5	54	9.5
3W	18	32.5	39	6	17	52.5	63	5.5
BT	33	27	12	4	12	42	33	2
TT	41	59	15	2	24	--	66	6
PH	17	70	65	4	17	65	66	9
HO	35	30	63	13	36	46	39	11
RZ	49	13	49	5	35	70	27	10

Subject 1, D Mission

	EVENTS/MIN HMD				EVENTS/MIN NOHMD			
	BLINKS	SAC H	SAC V	V SAC W/BLINK	BLINKS	SAC H	SAC V	V SAC W/BLINK
1W	24.5	33	48	9.5	28.5	59	63	13
3W	17.5	45	45.5	4	26.5	55.5	59.5	19.5
TT	39	39	26	5	25	105	70	18
PH	47	12	46	12	35	66	35	16
HO	34	32	71	13	36	44	47	14

Table 7

Subject 5, A Mission

	EVENTS/MIN HMD				EVENTS/MIN NOHMD			
	BLINKS	SAC H	SAC V	V SAC W/BLINK	BLINKS	SAC H	SAC V	V SAC W/BLINK
1W	17.5	17	18	8.5	29.5	44	50	25
2W	18.5	17.5	24	6	24.5	31	28.5	30.5
TH	34	40	71	25	37	51	61	35
PTH	25	36	57	21	38	47	71	25
TT	25	13	56	17	33	47	62	17
PH	13	8	58	12	25	36	97	18
HO	11	0	19	3	17	29	66	23

Subject 5, C Mission

	EVENTS/MIN HMD				EVENTS/MIN NOHMD			
	BLINK	SAC H	SAC V	V SAC W/BLINK	BLINK	SAC H	SAC V	V SAC W/BLINK
1W	23.5	21.5	41.5	12	36	46.5	49.5	28.5
3W	24.5	21.5	33.5	7.5	33	43.5	65.5	30.5
TH	21	43	74	12	33	78	39	24
PTH	13	27	60	9	27	45	64	22

with these two patterns, thus, are blinks where eye position following blink termination is radically changed. In other contexts, we had observed that such blinks are also more likely to be associated with head movements than was true of more "conventional" blinks.

To the extent that the pilot has to acquire information from the instrument panel under NoHMD conditions, which, in the HMD condition, can be acquired from the information projected onto the visor, a tally of these blinks under NoHMD and HMD conditions should provide us with some information about the pilot's use of HMD displayed information.

One might suspect that the habit of checking the instrument panel, inculcated by thousands of hours of flying, would be difficult to abort, especially for pilots who have not had experience with using head-up displays. On the contrary, these results demonstrate the high level of adaptability of our pilots with respect to the use of novel, and presumably easier and more efficient, means of obtaining information about the aircraft. Both pilots, under all conditions, show a marked inhibition of such blink patterns when the HMD was available.

3.3 Blink/Saccade Concurrence; Manual Analyses.

Based on prior observations (and a hunch), we entertained the hypothesis that the concurrence of blinks and saccadic eye movements is more likely under high than under low work load conditions. This should be especially so when visual load is high, since during both a blink and a saccadic eye movement, there are periods of time when little visual information can be acquired. In the case of a blink, of course, no information can be acquired while the pupil is obscured by the eye lid; and with respect to saccades, there is marked suppression of visual input upon saccade initiation (and for a period preceding and following). This suppression, in fact, may persist beyond the point of saccade termination. For these reasons, the coincidence of these ocular events would maximize input time and thus increase efficiency.

The literature on this phenomenon has been restricted to the study of horizontal saccades. We know of no data on saccade suppression associated with vertical or oblique saccades. We suspect, however, that to the extent that saccade suppression is associated with central (nervous system), rather than peripheral (intra-ocular), mechanisms, the duration of suppression may be affected by central factors. Bartz (1966) has alluded to such a possibility in his brief discussion of "pre-saccade" suppression, the suppression of visual intake prior to the initiation of a saccade. Although it has not been studied, we may speculate that such pre-saccade suppression is affected by such central variables as "expectancy" and complexity of the information that is to be acquired. For example, pre-saccade suppression may be affected by the number of alternative locations to which the eye may be required to move following the presentation of a signal at one of several alternate locations. These speculations are relevant to our concern with the acquisition of information when it is available on the HMD, as compared to when such information has to be acquired via relatively large amplitude saccades, and, perhaps, head movements.

To the extent that information acquisition in the absence of the HMD is more difficult, this condition should be accompanied by a greater incidence of the co-occurrence of blinks and saccades. Carrying this argument further, we might predict that blinks may also be more frequently associated with oblique saccades in the NoHMD condition. To explore these possibilities, we have initiated an analysis of our abstracted data (blinks and saccades) for the coincidence of these events. As we develop our metric for this purpose, we will add coincidence of head movement to these measures.

Since there were marked differences between the HMD and NoHMD conditions, in the total number of blinks and the total number of saccades, we expressed the frequency of coincident blink/saccades in each condition as a proportion of the total number of saccades in that condition. This was done separately for horizontal and vertical saccades. Ideally, such an analysis would have separated blinks associated with horizontal, vertical, and oblique saccades. Because of constraints in time and analytic procedure, however, this was not done. There is, therefore, overlap between categories, i.e., the same blinks associated with oblique saccades also appear as occurring with horizontal and/or vertical saccades.

For exploratory purposes, we conducted such an analysis for Subject 5, ingress flight C, which involved a Threat under both HMD and NoHMD conditions. These results are presented in Table 8. The column headings require some explanation: The first column, labeled HSAC/ΣH, refers to the percentage of horizontal saccades accompanied by a blink. For the first and second waypoints (1W and 2W) the duration of the periods was 120 s, 60 s before and 60 s after the waypoint, whereas for Threat and Post-Threat, it was only the 60 s period following the announcements of these events.

For the first HMD waypoint (1W), 32% of horizontal saccades had an associated blink, while in the NoHMD condition, that figure was 61%. In the second column the

TABLE 8

CO-INCIDENCE OF SACCADES AND BLINKS UNDER HMD AND NoHMD CONDITIONS

HMD

	H SAC / Σ H	V SAC / Σ V	H SAC / Σ B	V SAC / Σ B	COINC SAC / H+V SAC	OBLIQUE SACC W/BLINKS / H+V SAC
1W	32	29	30	51	17	38
2W	30	21	27	29	15	50
TH	28	16	57	57	17	43
PT	44	15	92	69	22	47
BT	29	22	18	50	11	2
TT	21	14	21	57	10	1
PH	8	10	8	33	19	2
HO	17	5	8	15	4	--
RZ	33	4	15	15	5	4

NoHMD

	H SAC / Σ H	V SAC / Σ V	H SAC / Σ B	V SAC / Σ B	COINC SAC / H+V SAC	OBLIQUE SACC W/BLINKS / H+V SAC
1W	61	53	79	72	25	75
2W	34	47	46	92	27	48
TH	22	62	51	73	19	55
PT	47	30	78	70	18	55
BT	46	38	67	70	27	16
TT	55	36	82	74	21	15
PH	58	22	73	47	15	10
HO	31	16	45	59	19	7
RZ	41	15	65	57	18	6

same transformation is performed for blinks associated with vertical saccades. (We should point out that we are using the term "saccade" rather loosely here, since our criterion for saccade identification allowed eye movements considerably slower than we generally require of saccades, e.g., pursuit and glissade movements.) In order to include saccades that would otherwise be confounded with blinks, as described above, we identified as vertical saccades, a shift in eye position following blink termination perceptibly different from the position preceding blink initiation. We estimate that if the smallest saccade accepted by our computer algorithm was 2° of arc, then we accepted as meeting our criterion any vertical position shift exceeding 4° during a blink.

The second column performs the same analysis for blinks co-incident with vertical saccades (as defined above). Again, for 1W, the percentage of co-incident blinks and saccades is considerably greater in the NoHMD than in the HMD condition.

The next two columns (3 & 4) present the percentage of coincident blinks/saccades, using total number of blinks in the denominator. Whereas the earlier measure represented that proportion of (all) saccades that were accompanied by blinks, this value is the proportion of (all) blinks that were accompanied by saccades. Column 5 evaluates oblique saccades (i.e., the coincidence of horizontal and vertical saccades) by dividing such coincident saccades by the total number of horizontal and vertical saccades. The last column again concerns blinks: the ratio of blinks that co-occur with coincident horizontal and vertical saccades, divided by the sum of all horizontal and vertical saccades.

Referring to Table 8, the analysis of the two-minute periods around waypoints 1 and 2 indicates that in all 12 cases the percentages are higher for the NoHMD (lower section of table) than for the HMD condition (upper section). The five refuel segments show similar unanimity in favor of the NoHMD condition. For the Threat and Post Threat conditions, we find the effect only slightly less uniform; in 9 of the 12 comparisons, the NoHMD percentages are larger than the HMD percentages.

4.0 Conclusions

What conclusion do we draw from this analysis? If, as we suspect, the coincidence of blinks and saccades is related to task complexity, then, for this subject, we can infer that flying under the NoHMD condition is a more complex or higher work load task. The higher blink rate under the NoHMD condition cannot account for this effect, since it is effectively counterbalanced by an even greater increase in saccades in both the horizontal and vertical planes (see Table 7).

We also have suggestive evidence that such coincidence of blinks with saccades is more prevalent with oblique than single plane saccades (compare the last column of Table 8 with the first two columns.) We believe that the actual differences in these percentages would have been larger had data for oblique saccades not also been included in the analyses involving the horizontal and vertical saccades.

We had expected that the Threat and Post-Threat conditions might impose higher work load on the pilot than the navigational checks and course changes associated with crossing of waypoints. Our data do not indicate this to be the case. The coincidence percentages are not uniformly higher under Threat than waypoint conditions.

Tables 9 and 10 take the above analysis one step further by deriving a single summary measure directly comparing the HMD and NoHMD percentages as they had been derived for Table 8. The summary measure contains the percentage for the NoHMD condition in the numerator and the sum of the two percentages in the denominator. Thus, a resultant value in excess of 50 indicates a higher percentage for the NoHMD condition. This analysis was conducted for two ingress and two refuel missions for subject 1 (who had no threats presented on any of his ingress missions) and two ingress missions with threats, as well as two refuel missions for subject 5.

For all four ingress missions, the waypoint segments demonstrate consistently higher ratios under the NoHMD, as compared to the HMD conditions. Of the 18 measures obtained for each mission, 15 and 18 exceed 50% for Subject 1, and 15 and 18 exceed 50% for Subject 5. We interpret these results as indicating that work load is higher under the NoHMD condition.

TABLE 9

COMPARISON OF NoHMD WITH HMD CONDITIONS FOR SUBJECT 1
(NoHMD/NoHMD + HMD) X 100

B Mission

Σ BLINKS	Σ SACCADES HOR	Σ SACCADES VER	COINC BL / Σ SACC HOR	COINC BL / Σ SACC VER	COINC BL / Σ BLINKS HOR	COINC BL / Σ BLINKS VER	COINC H+Vs / Σ SACC	V SAC W/BLINKS
1W 48	66	69	63	90	78	96	64	86
3W 49	62	62	61	56	72	69	63	48
BT 27	61	73	21	40	45	77	68	33
TT 37	--	81	--	75	--	58	--	75
PH 50	48	50	46	68	44	69	50	69
HO 51	61	38	57	69	65	58	59	46
RZ 42	84	36	46	79	87	73	68	67

D Mission

Σ BLINKS	Σ SACCADES HOR	Σ SACCADES VER	COINC BL / Σ SACC HOR	COINC BL / Σ SACC VER	COINC BL / Σ BLINKS HOR	COINC BL / Σ BLINKS VER	COINC H+Vs / Σ SACC	V SAC W/BLINKS
1W 54	64	57	72	60	72	60	62	58
3W 60	55	57	65	75	65	75	64	83
TT 39	73	73	46	48	46	48	61	78
PH 43	85	43	58	43	58	43	64	57
HO 51	58	40	79	54	79	54	57	52

TABLE 10

COMPARISON OF NoHMD WITH HMD CONDITIONS FOR SUBJECT 5
(NoHMD/NoHMD + HMD) X 100

A Mission

Σ BLINKS	Σ SACCADES HOR	Σ SACCADES VER	COINC BL / Σ SACC HOR	COINC BL / Σ SACC VER	COINC BL / Σ BLINKS HOR	COINC BL / Σ BLINKS VER	COINC H+Vs / Σ SACC	V SAC W/BLINKS
1W 63	72	74	40	39	56	66	39	75
2W 57	62	54	67	77	74	72	74	84
TH 57	78	53	47	74	70	36	66	58
PH 60	57	55	41	43	59	45	43	54
TT 57	78	53	47	74	70	36	66	50
PH 66	82	63	52	74	82	56	70	60
HO 61	100	78	--	--	--	63	--	89

C Mission

Σ BLINKS	Σ SACCADES HOR	Σ SACCADES VER	COINC BL / Σ SACC HOR	COINC BL / Σ SACC VER	COINC BL / Σ BLINKS HOR	COINC BL / Σ BLINKS VER	COINC H+Vs / Σ SACC	V SAC W/BLINKS
1W 61	68	70	66	65	72	59	60	70
2W 57	67	66	53	69	63	76	64	80
TH 61	64	35	44	79	47	56	53	66
PT 68	63	52	52	67	46	50	45	71
BT 55	74	51	61	63	79	58	77	63
TT 71	78	55	72	72	80	56	68	62
PH 71	76	60	91	69	90	59	44	62
HO 63	84	67	65	76	85	80	83	87
RZ 64	86	63	55	79	81	79	78	90

D. HEAD AND EYE MOVEMENTS; LITERATURE REVIEW

Timing of Head and Eye Movements

The literature on the relationship between head and eye movements under relatively "normal" conditions is scarce indeed. If by "normal" conditions we mean situations involving the dividing of attentional and other resources between a number of tasks, only one published study meeting such criteria can be found (Mourant & Grimson, 1977). If we include conditions where performance of a single task is required, we find a few more (Bartz, 1966; Barnes, 1977; Bizzi, 1974; Calhoun, Arbak & Janson, 1986; Gresty, 1974; Robinson, 1979; and Robinson, Koth & Ringenbach, 1976).

Mourant and Grimson (1977) collected eye and head movements of subjects driving under normal highway traffic conditions. They focused on the use of rear view mirror gazes. Two patterns of mirror gaze were described: a "classical" and a "predictive" pattern. The classical pattern involved eye movements initiated prior to head movements, while in the predictive pattern, head movements preceded eye movement initiation. They obtained approximately twice as many predictive than classical patterns in their nine subjects. The average latency for the classical pattern was approximately 45 msec, a latency that is comparable to that reported by Bizzi (1974) for the monkey. For the predictive pattern, they report an average latency of 90 msec between head and eye movement initiation. On the basis of data presented in the paper, it appears to us that the 90 ms latency reported is not representative; it overweights data collected in one of the four conditions of the experiment. That is, average latency for each of the four conditions was 66, 161, 64 and 68 ms. Excluding the "aberrant" condition, the average is 66 ms, which, perhaps, is a better basis for estimating predictive latency. Nevertheless, Mourant & Grimson quote an unpublished paper by Robinson and Subelman (1975) involving dual task performance, where subjects had to monitor a display at right angles to a central control task. These authors report that 63% of the head-eye movement patterns were predictive in nature with a latency of 117 ms. Clearly, the conditions favoring the predictive pattern, and the saccade/head movement time relations involved, are still unresolved.

Studies involving the measurement of eye and head movements where task requirements are simple, most frequently report the classical pattern. Extrapolating from the figure presented in Bartz (1966), it appears that the head movement follows eye movement initiation by approximately 100 msec.

Gresty (1974) does not report the time difference between saccade and head movement initiation. Extrapolating from his average values, head movements are initiated approximately 68 msec after saccade initiation. Robinson (1979) reports that latencies range between 0 and 50 msec, while Robinson, Koth, & Ringenbach (1976) report latencies of approximately 50 msec.

Only one study, Calhoun, Arbak & Janson (1986), reports latencies considerably longer than the above. Utilizing a task where head and eye movements were in the VERTICAL plane (all of the above mentioned studies dealt only with horizontal plane movements), these authors report latencies of 440 ms between eye and head movement initiation. They suggested that "system delay" in calculating eye/head position shifts can be on the order of 200 ms. However, subtracting 200 from 440 still leaves their latencies outside the range reported in the other studies reviewed here. These authors also report on the occurrence of the predictive pattern in 17% of trials. However, 70% of the data were contributed by one subject (N = 8). Gresty (1974) reported that one of his subjects demonstrated the predictive pattern, with saccadic eye movements following head movement initiation, by about 40 ms. This subject wore contact lenses, and attributed this pattern to "...the fact that if she made fast eye movements, her contact lenses might fall out." (p. 399).

From these studies, one can conclude that, in general, gaze shifts involve the initiation of saccades approximately 50 ms before the head starts to move. Robinson, Koth and Ringenbach (1976) correlated saccade and head movement latencies, with respect to stimulus presentation. The average correlation was 0.92, suggesting the high likelihood that both are controlled by the same central nervous system center, a conclusion also arrived at by Vossius (1972).

That the pattern of eye and head movements cannot be completely accounted for by simple quantitative bioengineering variables is well attested to in the literature reviewed above. For example, Robinson, Koth & Ringenbach (1976) report that the pattern of eye and head movements is affected by eye movement calibration procedures. "It might be noted here, that initial eye calibration procedures used a bite bar and the procedure was found to inhibit head movements on later trials after it had been removed." Robinson (1979) points out that the likelihood of occurrence of head movements in the acquisition of peripheral information is affected not only by the angular distance between current eye position and the target display but also by the time necessary to acquire information from the peripheral display, and by the anticipation of gaze shifts to other displays. In a similar vein, we have observed that the pattern of eye-head coordinations may be markedly different depending on whether information can be acquired rapidly, or is time consuming, or whether the movement returns gaze to a central fixation position following peripheral information acquisition. Thus, the nature of the information to be processed, as well as immediately preceding task requirements, may be as important in determining the patterning of eye-head movements as the biomechanical control mechanisms affecting gaze shifts.

Our studies provide some additional information concerning eye-head movement dynamics. In these studies, subjects had to acquire information from peripheral locations to the left (L) or right (R) of the central fixation point. Specifically, the locations were 45° L, 15° L, 0°, 15° R, and 45° R. Two levels of task requirements were utilized. One involved the detection of a peripheral signal, a letter, following a centrally presented letter. In the "Detect" condition, the subject was required to indicate whether or not a peripheral signal had been presented following termination of the central signal. In the "Identification" condition, he was to determine whether the peripherally presented letter was the same as or different than the centrally presented one.

Under the Detect condition, we obtained very few eye movements (prior to responding), and no head movements. Under the Identification condition, there were eye movements to foveate all peripheral targets, but few head movements. Based on the work by Sanders, we had expected that most of the trials involving target eccentricities of 45° would be accompanied by head movements. On trials where head movements did occur, the average latency of head movements (following onset of the peripheral target) was 50 ms after saccade initiation. Head movement returning gaze to the central location, in anticipation of the next centrally presented signal, was much more variable with respect to eye movements. Head movement velocities appeared to be considerably slower, and head movement initiation frequently preceded eye movement initiation by 100 ms or more. We would be loath to call the latter head movements "predictive," in the sense that Mourant and Grimson (1977) used that term. Regardless of what one wishes to call these head movements, the fact that there is more than one pattern of coordination of eye and head movements, rules out simplistic explanations of such activity, and stresses the possibility that their temporal patterning can be used to make inferences about aspects of information processing.

A second variable of concern deals with the duration of head movements. This parameter has been investigated in two studies. Zangemeister, Jones & Stark (1981) evaluated head movements under conditions where subjects were instructed to move their heads (not gaze) as rapidly as possible between targets that were from 2° to 140° apart (no eye movement data were collected in this study). Gresty (1974) reported on head movement duration to stimuli presented at eccentricities up to 81.7° left and right of center. Both studies report head displacement durations of about 450 ms, with duration invariant with respect to amplitude. What one can see in the

Zangemeister, et al., paper is that head movement duration is more variable for smaller amplitude movements.

E. HEAD MOVEMENT ANALYSIS - MANUAL

1.0 General information

Head movement data collection utilized the Polhemus head tracking system. As utilized in the present application, HORIZONTAL and VERTICAL plane head movements were digitized at a sampling rate of 20/sec (50 ms sampling period). They were then D/A converted for storage on magnetic tape. Two channels of head movement data were thus used in the current analysis.

Data for all subjects were strip charted. Both horizontal and vertical eye movements and horizontal and vertical head movements were charted concurrently. Relevant voice information, where it was intelligible, was identified on the strip charts.

Segments of data for each subject were digitized at a rate of 100 or 200 samples/sec and stored on disks. For our initial head movement analysis, segments of data with readily discernible head movements were digitized for subsequent analysis.

Data reduction for all data utilized our MARLAB program. The analysis of all head movement data utilized manual point setting routines to identify initiation and termination of head movements, as well as the amplitude of such movements. Where head and eye movement and blink information was to be abstracted, we either used a manual point setting routine for all four channels of data, or the oculometric analysis was conducted semi-automatically.

The semi-automatic analysis involves defining parameters that are to be used for defining vertical EOG activity as eye blinks, and a second set of parameters to define horizontal EOG activity as saccades. These algorithms are then applied to the data displayed on a monitor (1000 data points at a time), and the operator can perform edit functions on such data.

The integration of eye and head movement data was done manually. The data reduction process (at this time) is, thus, a slow and labor-intensive effort.

2.0 Selection and Categorization of Data

The analyses described in this section were done manually; data for all flights were strip charted and head movements were identified by examining the strip chart. For each flight, we identified head movements in the horizontal and vertical plane, as well as the conjoint occurrence of both horizontal and vertical movements. Our criterion for including a head movement in this analysis was that it exceed 10° of arc (estimated) in either the horizontal or vertical plane.

The number of head movements (vertical, horizontal, and/or conjoint) for both the INGRESS and REFUEL missions were abstracted and summarized based on the following patterns:

1.	UP only (U)	5.	RIGHT and UP (R+U)
2.	DOWN only (D)	6.	RIGHT and DOWN (R+D)
3.	RIGHT only (R)	7.	LEFT and UP (L+U)
4.	LEFT only (L)	8.	LEFT and DOWN (L+D)

3.0 Presentation and Analysis of Data

The data are presented in two formats since the absolute number of head movements differed markedly both across subjects and across conditions (HMD or noHMD; INGRESS or REFUEL missions). First, the total number of all head movements for each of the five subjects under each of the four conditions are presented in Table 11. Since the pilots did not necessarily fly an equal number of missions, the totals are "corrected" for the number of missions flown.

We were interested in determining whether there was anything systematic about the distribution of head movement patterns when frequency of head movements differed as a function of condition. If the number of head movements under the noHMD condition was twice as large as under the HMD condition, for example, we were interested in determining whether the increase was spread equally across the eight head movement patterns, or were certain patterns favored?

Two analyses were conducted. The results of the first, depicted in the lower portion of the bar graphs (see Figures 13 - 22), expressed activity in each of the eight patterns as a percentage of the sum of all head movements within either HMD or noHMD conditions. The amplitudes for any one condition should sum to 100%.

The results of the second analysis, depicted in the upper right hand corner of the bar graphs (see Figures 13 - 22), depicts summary data, again using the sum of all head movements as the denominator. The numerator for TOTAL RIGHT included R, R+U, R+D; for TOTAL LEFT, the numerator included L, L+U, L+D; for TOTAL UP, the numerator included U, L+U, R+U; and for TOTAL DOWN, the numerator included D, L+D, R+D. Since the same items are included in a number of the TOTAL values, these amplitudes do <u>not</u> sum to 100%.

HEAD MOVEMENT ANALYSIS

SUBJECT 1; HMD vs. NO HMD; REFUEL

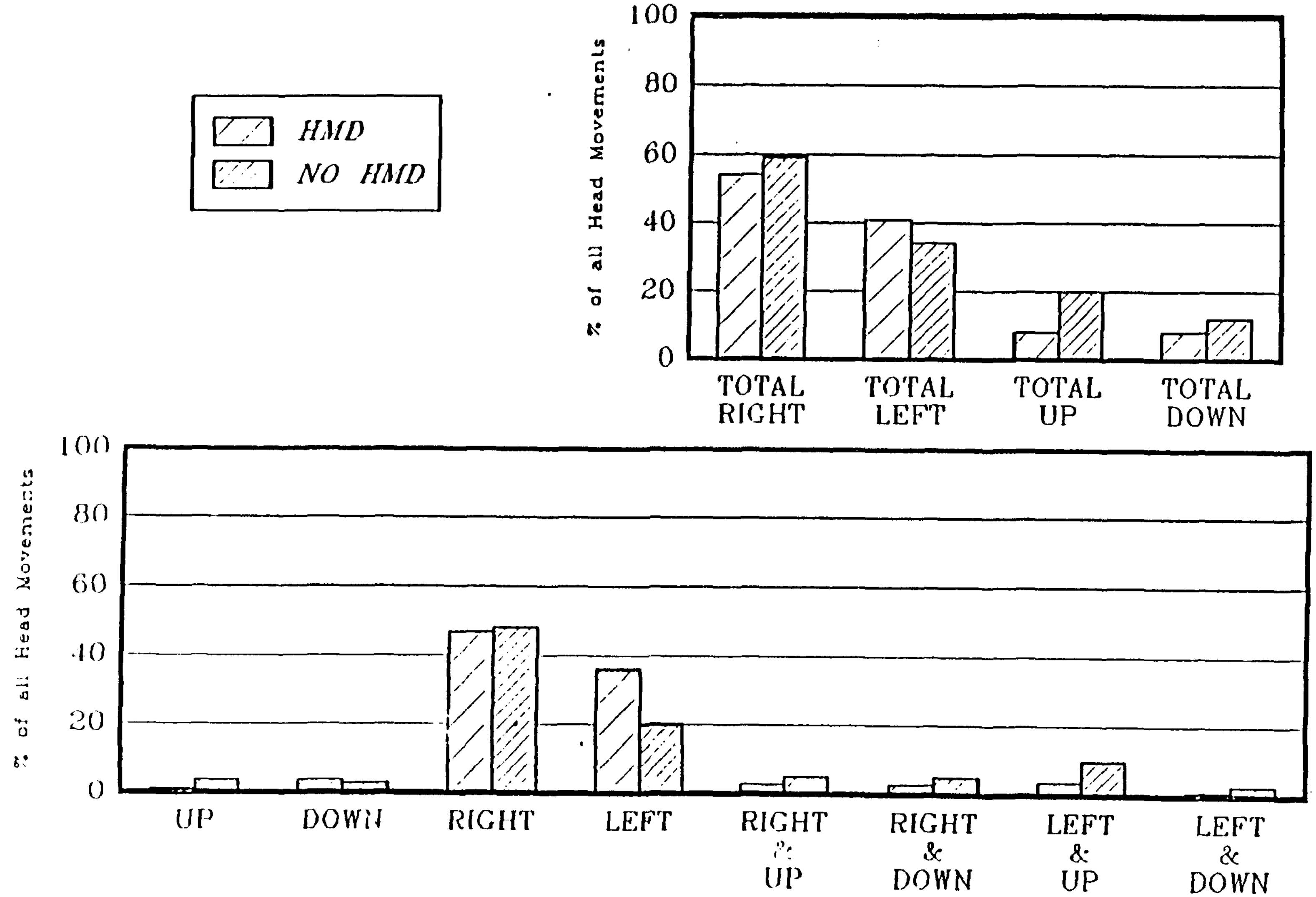


Figure 13

HEAD MOVEMENT ANALYSIS

SUBJECT 1; HMD vs. NO HMD; INGRESS

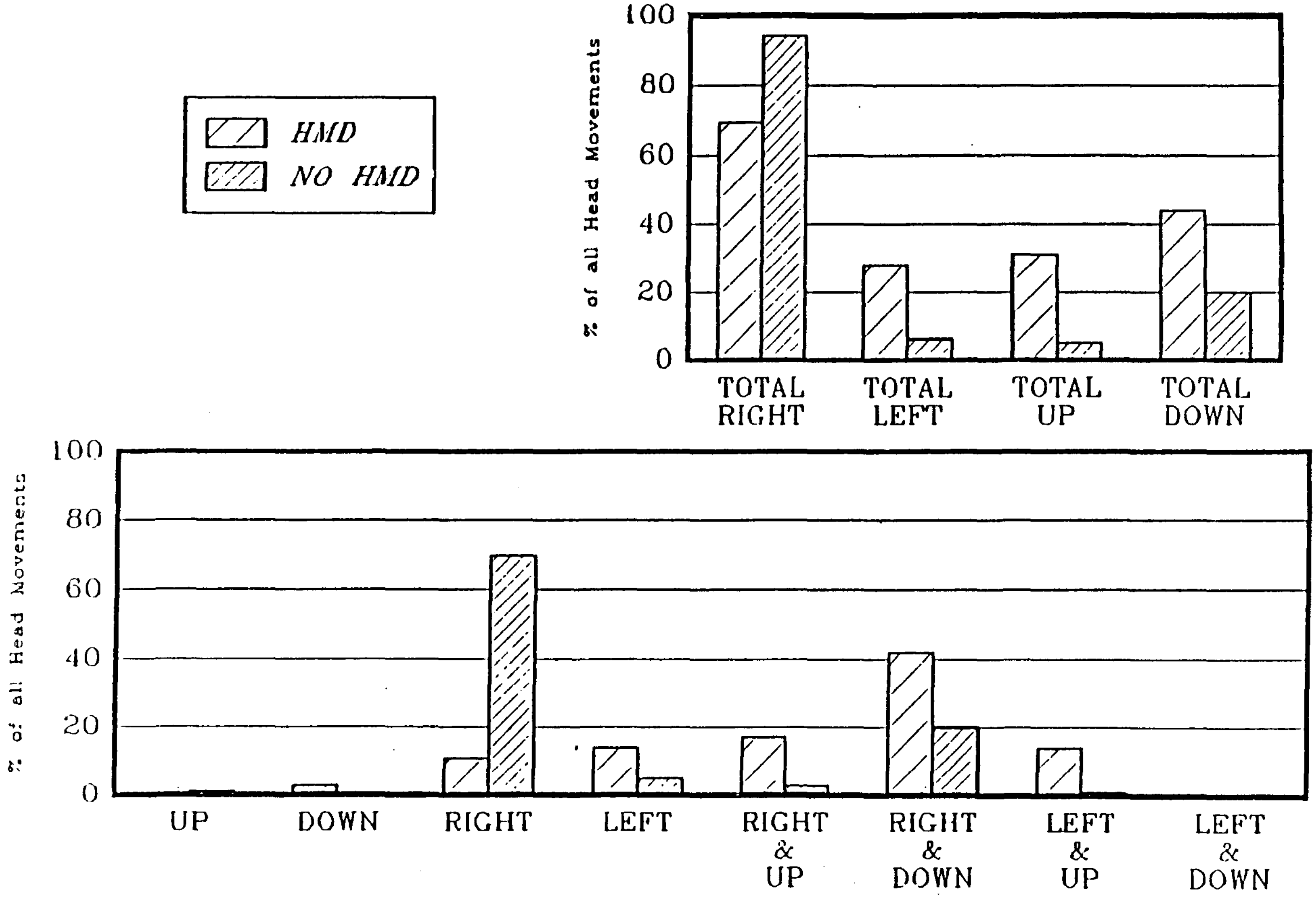


Figure 14

HEAD MOVEMENT ANALYSIS

SUBJECT 2; HMD vs. NO HMD; REFUEL

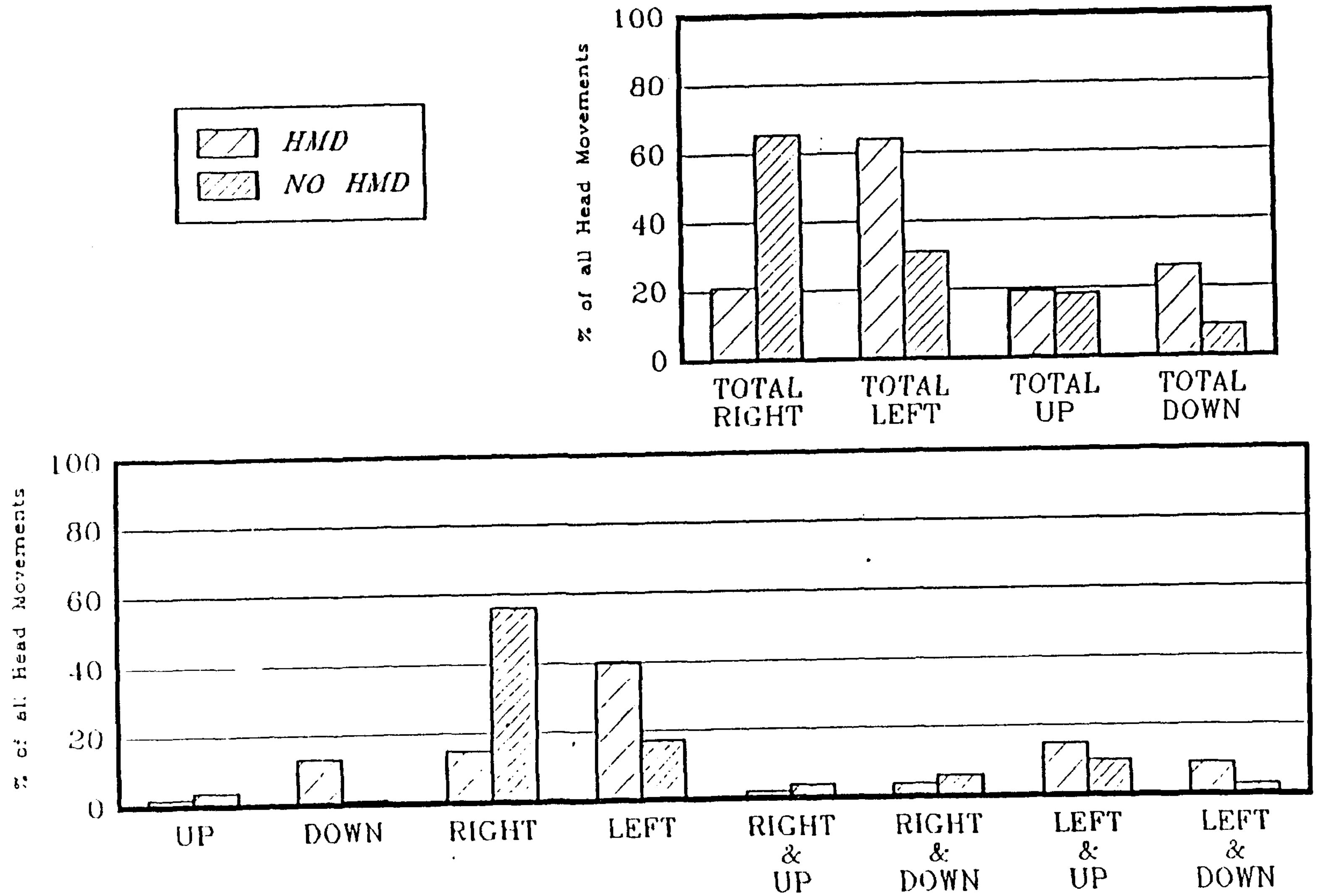


Figure 15

HEAD MOVEMENT ANALYSIS

SUBJECT 2; HMD vs. NO HMD; INGRESS

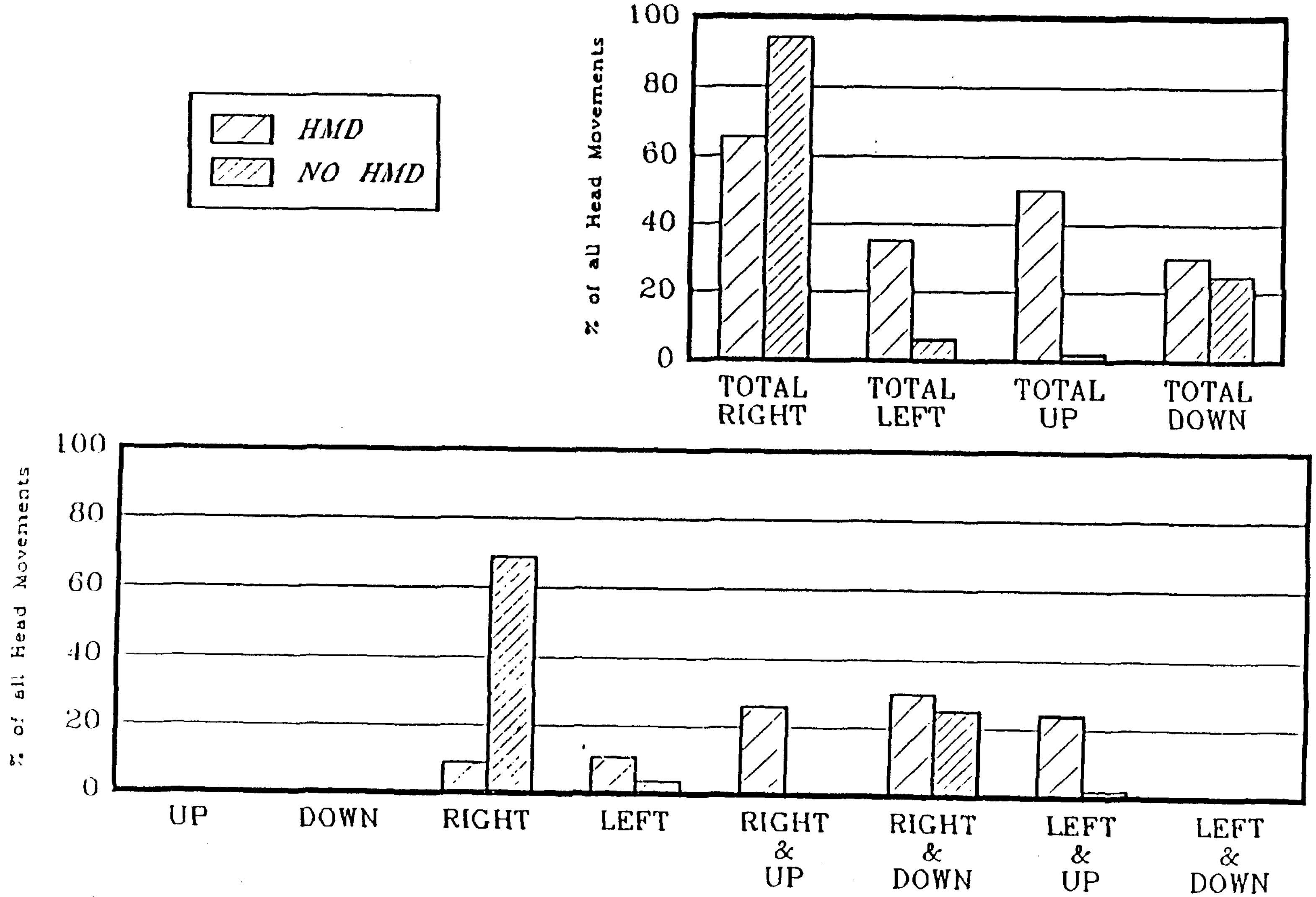


Figure 16

HEAD MOVEMENT ANALYSIS

SUBJECT 3; HMD vs. NO HMD; REFUEL

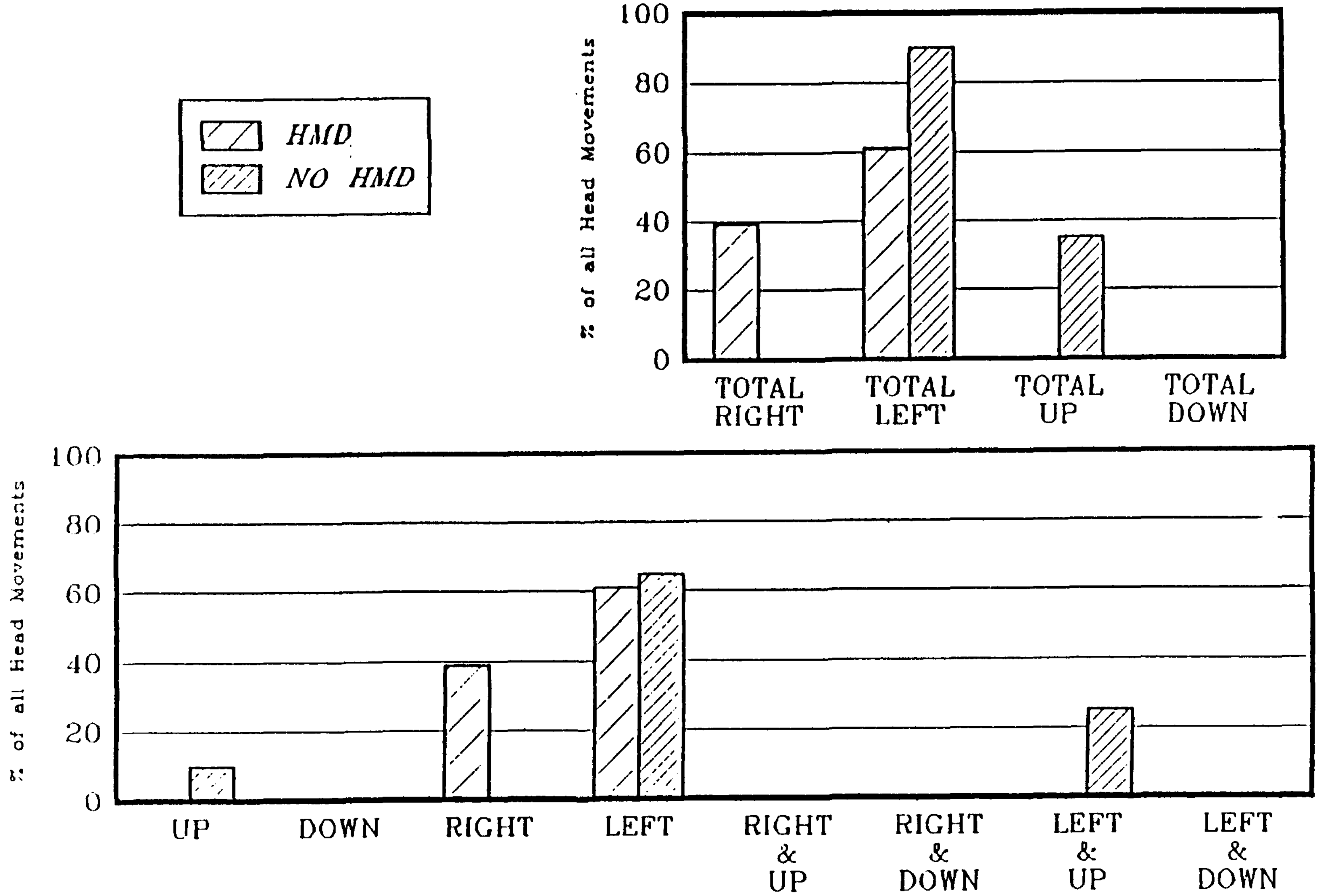
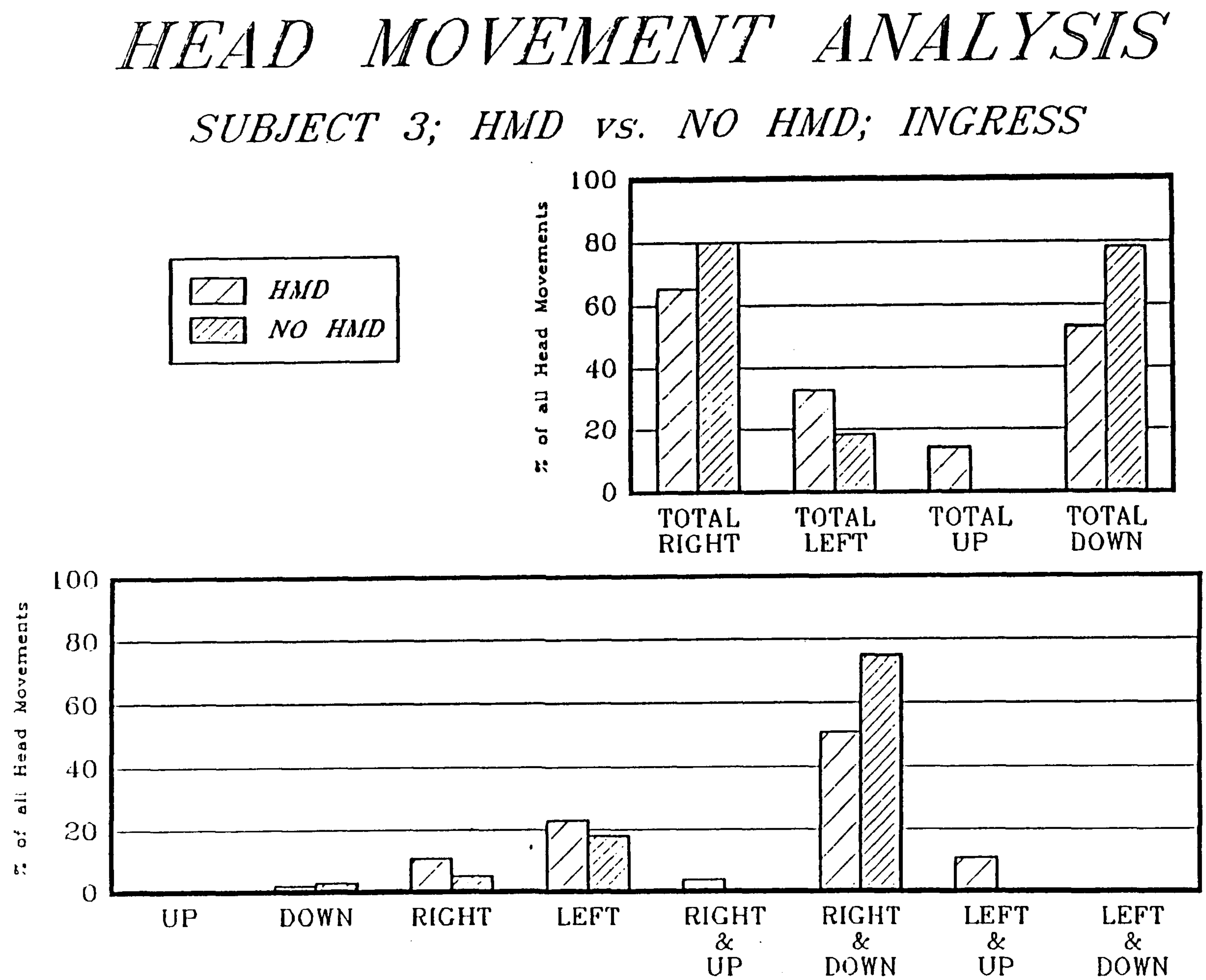


Figure 17



HEAD MOVEMENT ANALYSIS
SUBJECT 3; HMD vs. NO HMD; INGRESS
HMD
NO HMD
% of all Head Movements
100
80
60
40
20
0
TOTAL RIGHT
TOTAL LEFT
TOTAL UP
TOTAL DOWN
UP
DOWN
RIGHT
LEFT
RIGHT & UP
RIGHT & DOWN
LEFT & UP
LEFT & DOWN

Figure 18

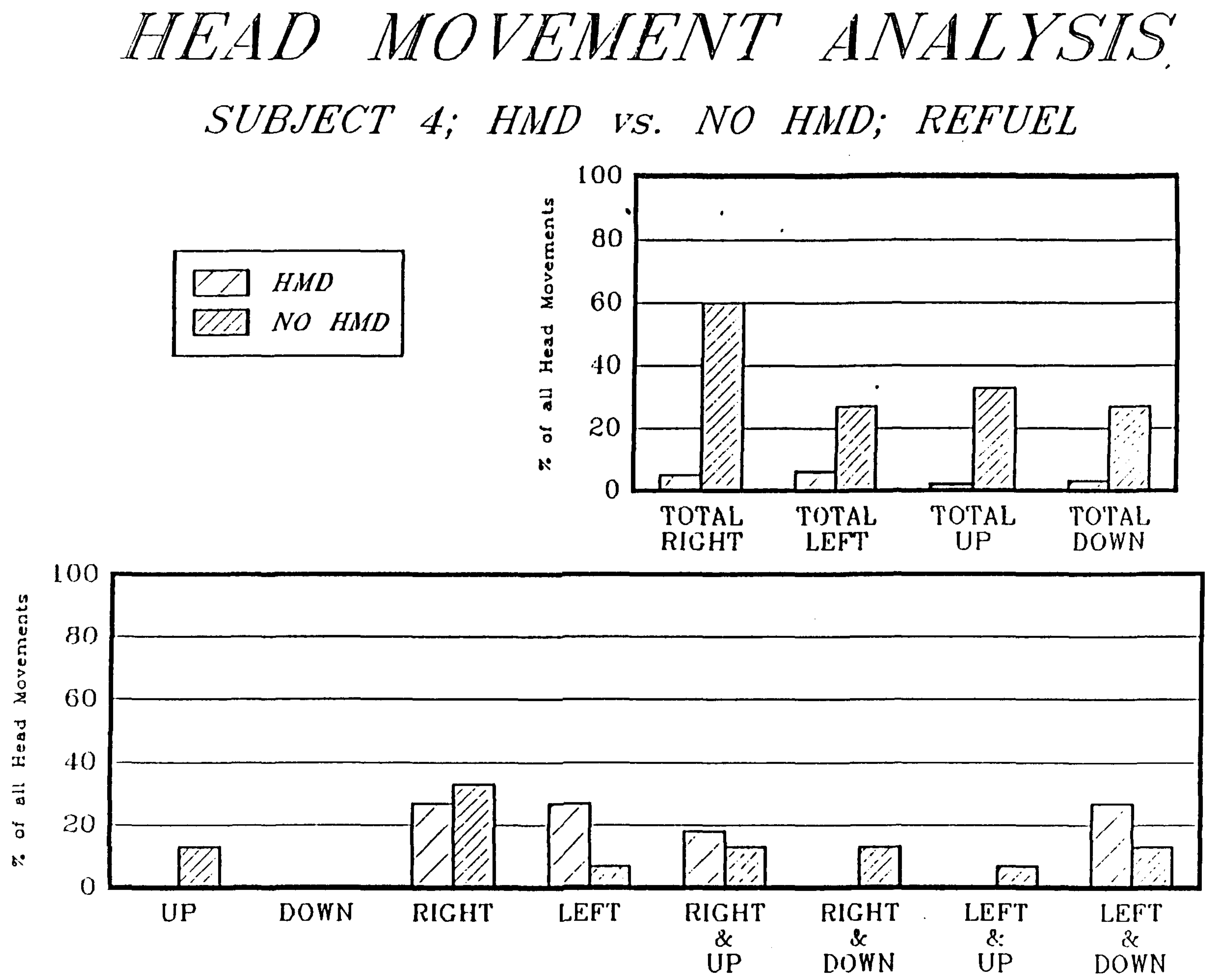

HEAD MOVEMENT ANALYSIS
SUBJECT 4; HMD vs. NO HMD; REFUEL
HMD
NO HMD
% of all Head Movements
100
80
60
40
20
0
TOTAL RIGHT
TOTAL LEFT
TOTAL UP
TOTAL DOWN
% of all Head Movements
100
80
60
40
20
0
UP
DOWN
RIGHT
LEFT
RIGHT & UP
RIGHT & DOWN
LEFT & UP
LEFT & DOWN

Figure 19

HEAD MOVEMENT ANALYSIS

SUBJECT 4; HMD vs. NO HMD; INGRESS

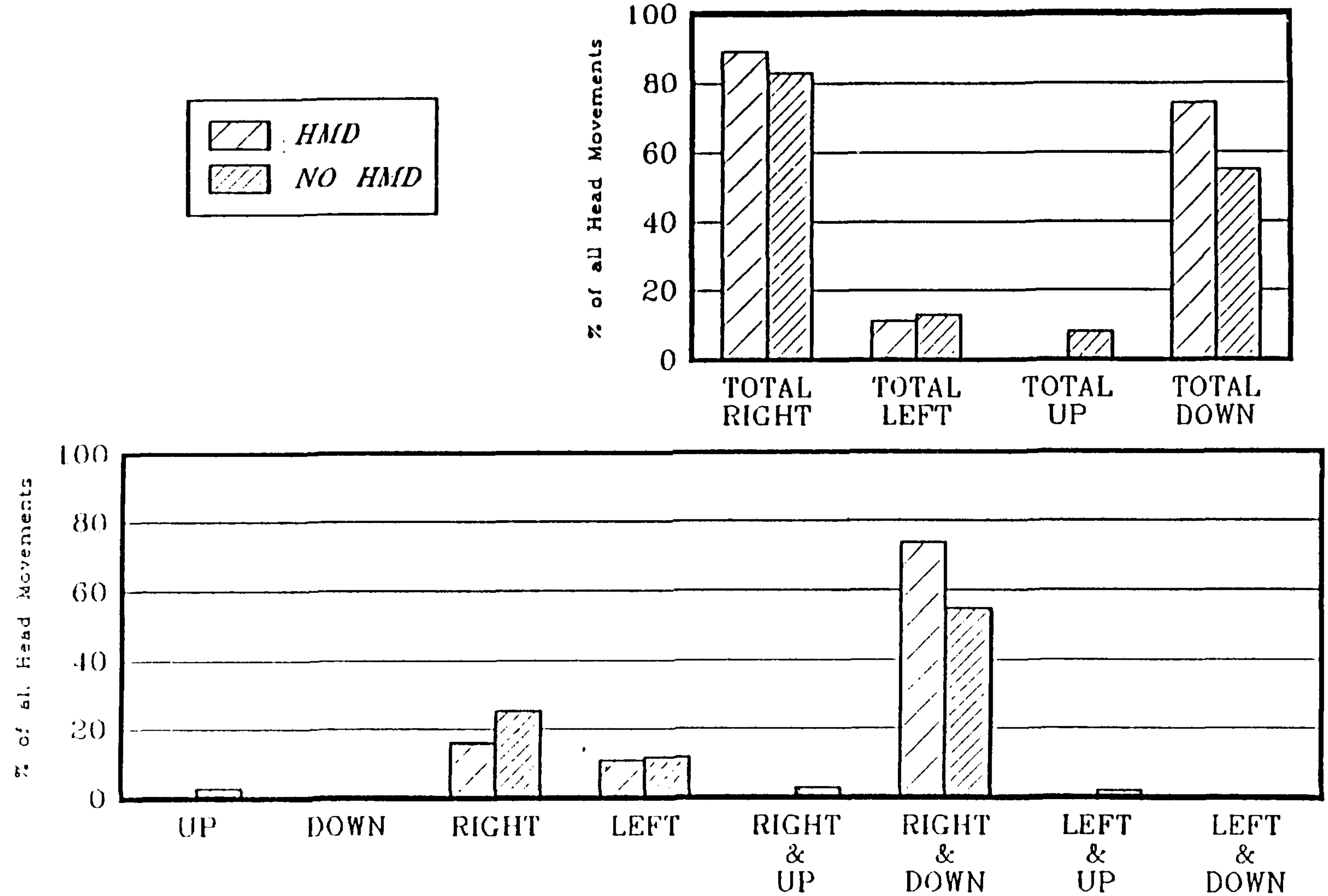


Figure 20

HEAD MOVEMENT ANALYSIS

SUBJECT 5; HMD vs. NO HMD; REFUEL

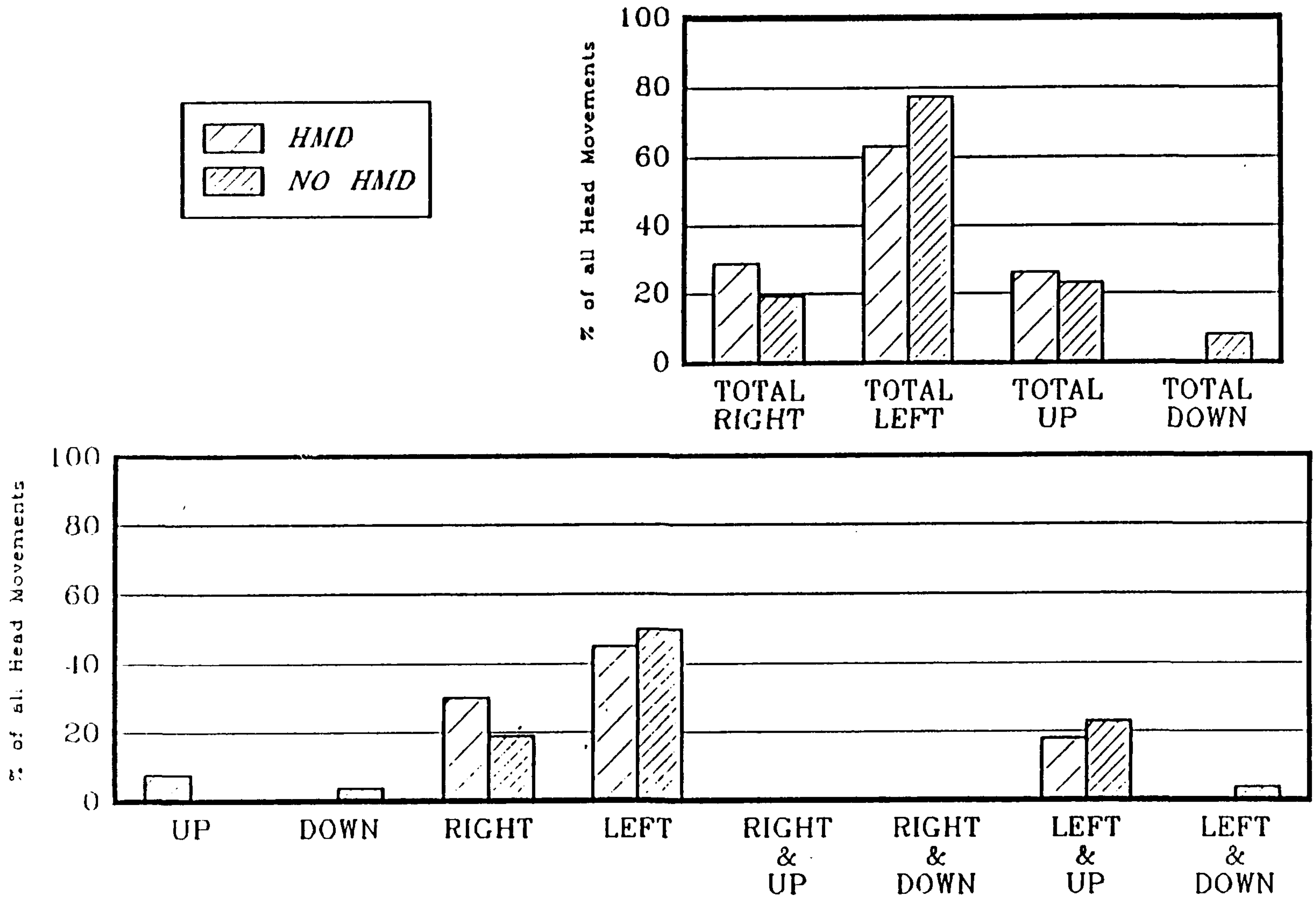


Figure 21

HEAD MOVEMENT ANALYSIS

SUBJECT 5; HMD vs. NO HMD; INGRESS

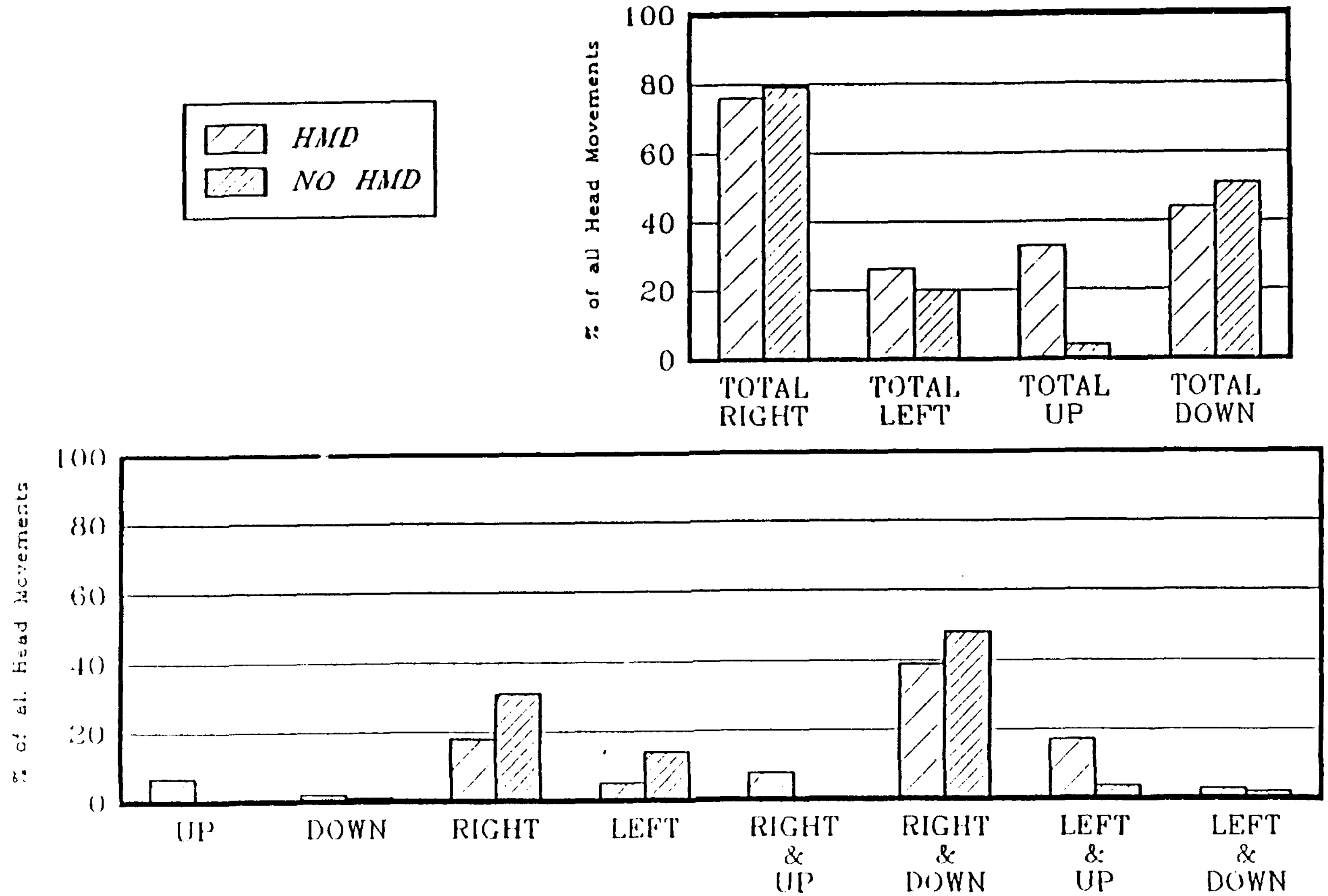


Figure 22

4.0 Results

4.1 Results Based Upon Total Head Movements

Examination of Table 11 makes it readily apparent that there are marked individual differences in the frequency of head movements across subjects (ranging from 11 to 220), and that the effect of the four conditions is not uniform across the five subjects. The first two subjects demonstrate a consistent pattern in that they make more head movements under the noHMD than the HMD condition, and make more head movements in the REFUEL as compared to the INGRESS flights.

Subject 4 shows a similar pattern, with more head movements under the noHMD than the HMD condition. However, this subject differs from subjects 1 and 2 in that he makes more head movements during INGRESS, as compared to REFUEL missions.

Subjects 3, 4, and 5 show a common pattern, in that they engage in more head movements during the INGRESS than the REFUEL missions.

The rather obvious conclusions which can be drawn from this rather crude analysis are that:

1) there are marked individual differences in the use of head movements associated with both INGRESS and REFUEL flights.
2) some pilots (three out of five) make markedly more head movements under the noHMD, as compared to the HMD condition.

We had expected that the HMD condition would lead to more head movements since, under this condition, the pilots would engage in more extensive search of their environment, having the normally stationary instrument information available on their visors at all times; this did not occur. We suspect that the reduction in head movements for the HMD condition reflects the fact that these pilots did make use of the information displayed on the HMD, but did not use the "released time" to engage in other visual search activity. Thus, pilots rapidly learn to make use of the information provided on the HMD. It is our suspicion that considerably more experience in flying with the HMD must occur before a pilot starts using the additional time available to engage in new patterns of visual search activity.

4.2 Results Based Upon Relative Head Movement Frequency

4.2.1 Head Movement Patterns During INGRESS Flights

Regardless of availability or non-availability of the HMD, the most frequent head movements were to the right or right coupled with a downward gaze. Four of the five subjects made a greater percentage of RIGHT ONLY head movements under the noHMD condition. Subjects 1 and 2, who showed the greatest increase in head movements from the HMD to the noHMD condition, demonstrate a markedly higher percentage of right head movements under the noHMD condition.

Analyses demonstrate that subjects 3, 4, and 5 make the largest proportion of their head movements to the RIGHT AND DOWN (presumably associated with looking at their maps), but the differences between the HMD and noHMD condition in this gaze shift is relatively small, suggesting that availability of the HMD had no effect on the frequency with which the pilot referred to his map during the flight. Two pilots, 3 and 4, make more than half of their head movements utilizing this pattern. The other item of note is the absence of pure UP, pure DOWN, and head movements to the LEFT AND DOWN, during INGRESS missions. Again, there are no differences between the HMD and noHMD conditions.

One can conclude, then, that for those subjects who make more head movements in the noHMD condition, the majority of these head movements involve gaze shifts in the horizontal plane to the right. Whether or not the HMD is available does not affect gaze shifts to the map. Further, there appear to be marked differences between pilots, with respect to the frequency with which they refer to their maps.

4.2.2 Head movement patterns during REFUEL flights

The head movement patterns for these missions were radically different from those in the INGRESS missions. In general, as one might expect, there were very few gazes to the RIGHT AND DOWN, the gaze shift associated with looking at the map. Additionally, comparison of INGRESS and REFUEL missions demonstrated that right head movements were not as dominant a pattern during REFUEL missions as was true for the INGRESS missions - left movements were as prominent as right movements.

There were no consistent patterns of head movements that discriminated between HMD and noHMD conditions across subjects.

TABLE 11

HEAD MOVEMENTS

	SUM OF ALL HM (CORRECTED FOR # FLIGHTS)				RANKING OF HM FREQUENCY			
	INGRESS		REFUEL		INGRESS		REFUEL	
SBJ	HMD	noHMD	HMD	noHMD	HMD	noHMD	HMD	noHMD
1	36	125	95	220	4	1	1	1
2	46	116	94	214	3	2	2	2
3	57	40	36	40	2	5	4	4
4	19	60	11	15	5	4	5	5
5	98	100	76	52	1	3	3	3

5.0 Summary

The above analyses demonstrated that consistent differences exist between the HMD and noHMD conditions associated with the INGRESS missions: pilots engaged in a greater percentage of rightward head movements in the INGRESS/noHMD condition. Although the availability of the HMD had no effect on gaze shifts to the RIGHT and DOWN (the location of the map), marked individual differences did exist with respect to such gaze shifts.

Additionally, the patterns of head movements associated with the REFUEL missions were markedly different from those associated with the INGRESS missions, in that there were more LEFT head movements, and fewer RIGHT and DOWN movements.

F. HEAD AND EYE MOVEMENTS

1.0 Quantitative Analysis; Horizontal Plane

A numbe. of patterns of horizontal eye movements in conjunction with head movements in the horizontal plane could be identified. The most common pattern, and one frequently referred to in the literature, involves a saccade followed by a slower eye movement, a "compensatory eye movement," in the opposite direction. It is presumed that the saccade in conjunction with the early phase of the head movement allows the observer to foveate the object. The slower backward (compensatory) movement of the eye is presumed to occur concurrent with a continued head movement, and allows the viewer to maintain the object in foveal view. These observations have generally been made in laboratory situations where the location of the item to be fixated is under experimenter control, and where the movement is restricted to the horizontal plane.

Our analysis of what subjects did under our flight simulation condition is considerably at variance with the above description. For subject #5, we sampled 25 horizontal eye-head movements where the eye movement involved a saccade followed by a slower compensatory eye movement in the direction opposite the saccade. Approximately an equal number of left- and right-going saccades and head movements were analyzed. We identified three points for each eye movement, and two points for each head movement. The three time points for each saccade were: initiation, saccade termination, and "compensatory eye movement" termination. The two head movement points identified were head movement initiation and termination. From these values were derived: median saccade duration (180 ms), compensatory eye movement duration (220 ms), and head movement duration (370 ms). Further, the median delay of head movement initiation, following saccade initiation, was 110 ms, and finally, the median time between compensatory eye movement and head movement termination was 100 ms.

Since saccade amplitude and head movement amplitude were not measured, amplitude cannot be related to duration. However, saccade duration medians of 180 ms are not unusual for large amplitude saccades, which we assume these were. Head movement duration is quite independent of head movement amplitude, and the durations obtained here were within the range normally reported.

The time between saccade and head movement initiation found under strict experimental conditions is on the order of 50 ms. Our value of 110 ms is well outside that range, but not unusual for studies involving somewhat more complex visual information acquisition tasks than those usually found in laboratory studies.

We were quite surprised, however, that unlike results reported in the literature, our compensatory eye movements did not terminate concurrently with head movement termination. The eye movements frequently terminated considerably before head movement termination (100 ms). Evaluating the time difference between head movement initiation and compensatory eye movement termination, we find the median head movement to be initiated approximately 60 ms before saccade termination. Thus, the compensatory eye movements start 60 ms into the head movement and may terminate long before the head movements ends.

This raises a major question for us concerning the issue of whether the backward drift of the eye is a compensatory eye movement made to maintain fixation on the object. Of course, we have not ruled out possible errors to account for this effect, and believe that this phenomenon needs to be studied under better controlled conditions than those available in a flight simulator.

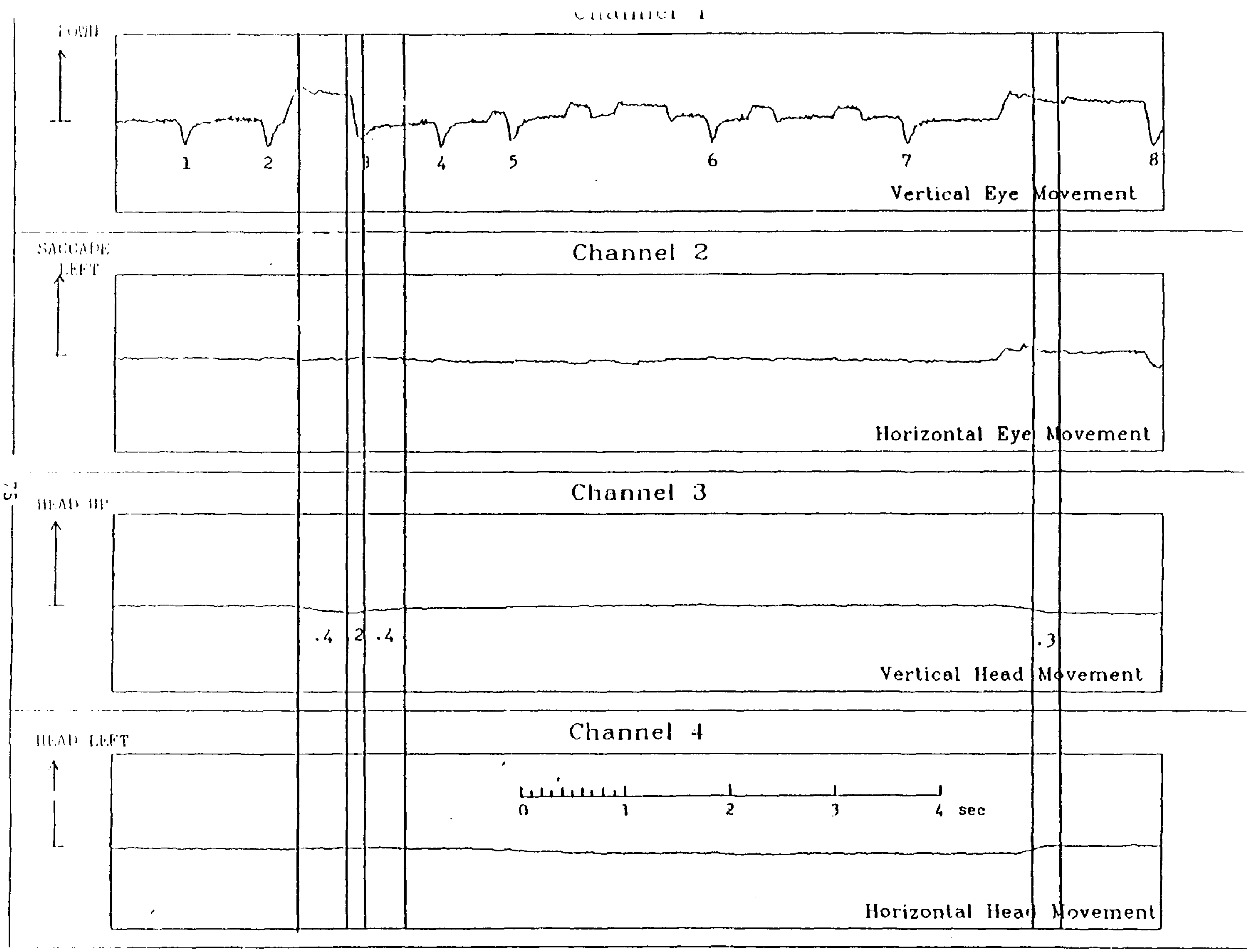
A second eye movement pattern seen in conjunction with head movements in the horizontal plane involved a saccade, followed by a slower eye movement (compensatory eye movement) in the same direction as the saccade, followed by a compensatory eye movement in the opposite direction. This pattern occurs less frequently than the one described earlier. When this pattern occurs, the head movement is most likely to be initiated during the second component, i.e., during the slow eye movement that continues in the direction of the immediately preceding saccade. This pattern appears to be less frequent than the first pattern, occurring about one third as often. In this pattern, most of the head movements are initiated during the slower eye movement (the one which follows the saccade). Saccade durations are consistently shorter in this pattern than in the first pattern, but the total time of the saccade and compensatory eye movement is longer than the saccade.

It is our impression that we can reliably predict that a head movement is present when either of these two patterns of horizontal eye movement are seen. In the vertical plane, we are considerably less secure about inferring head movements from the pattern of eye movements.

2.0 Qualitative Analyses, or, a Picture is Worth a Thousand Words

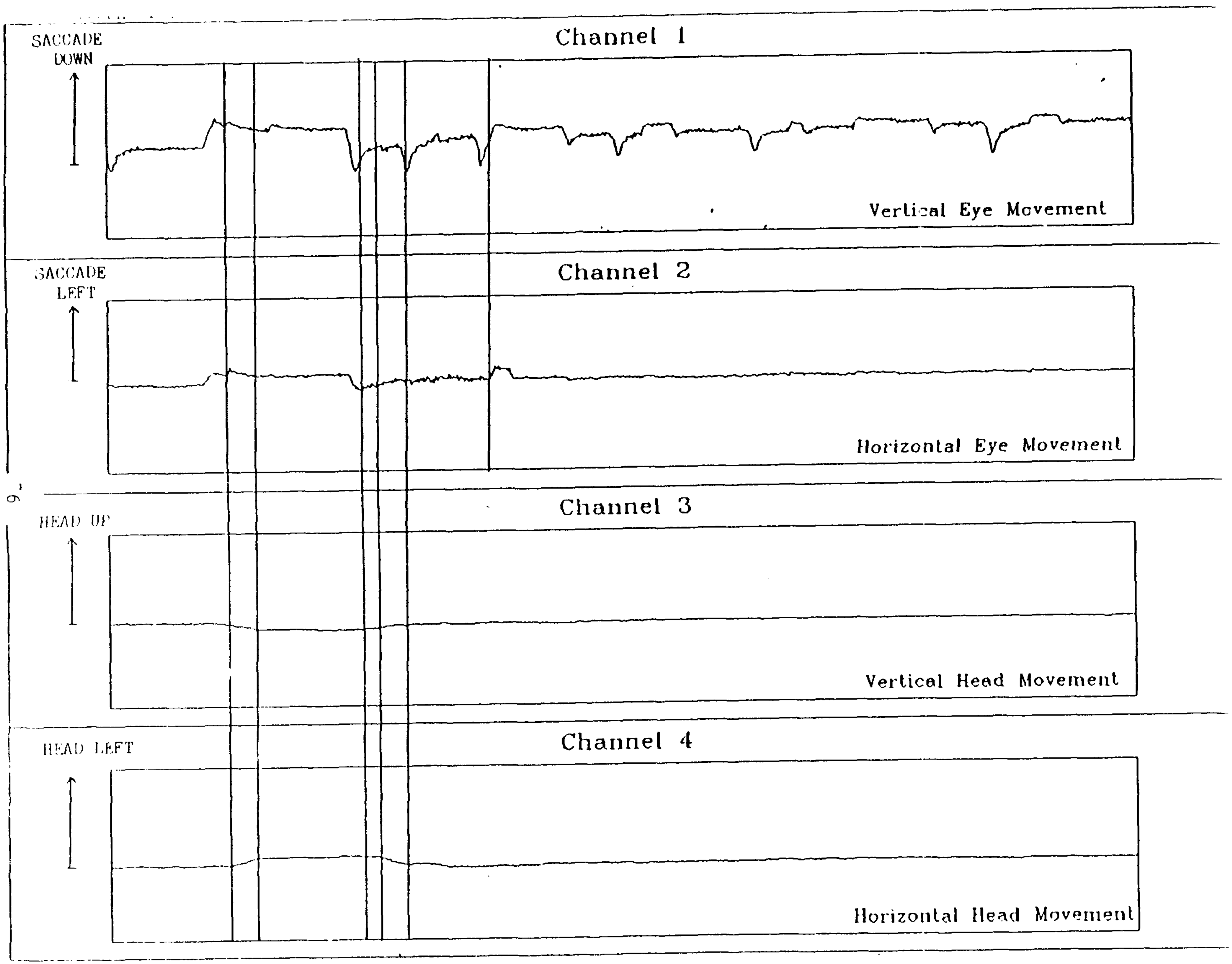
2.1 Computer Displays

Figures 23A to 23S are selected 10 second segments of computer-displayed data that contain both head and eye movements. The segments are from the flights of two subjects and were chosen to represent a variety of patterns of head and eye movements. No attempt at calibrating eye and head movement amplitudes was made; however, the same



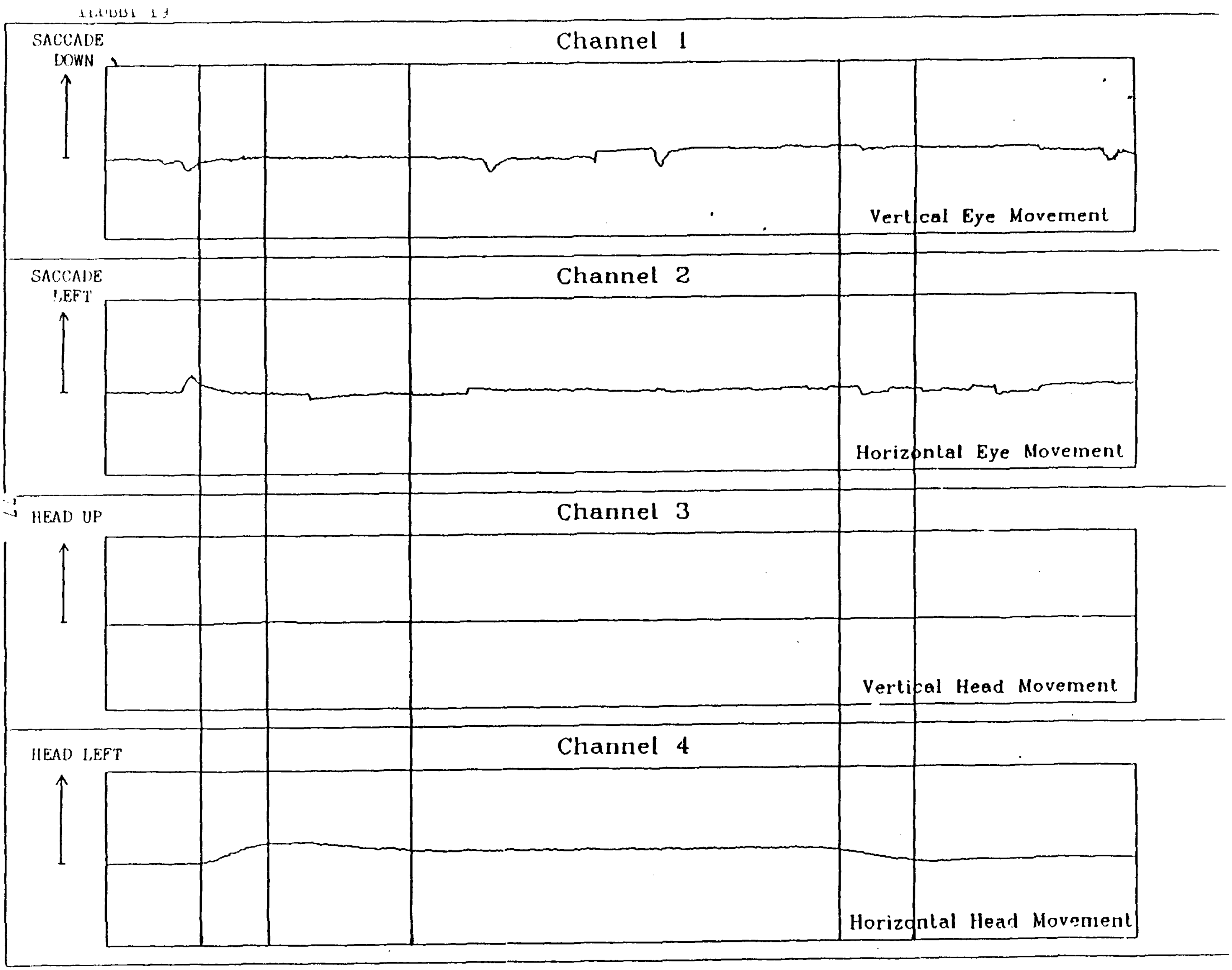
Channel 1
DOWN
1
2
3
4
5
6
7
8
Vertical Eye Movement
Channel 2
SACCADE LEFT
Horizontal Eye Movement
Channel 3
HEAD UP
.4
2
.4
.3
Vertical Head Movement
Channel 4
HEAD LEFT
0
1
2
3
4
sec
Horizontal Head Movement

FIGURE 23A



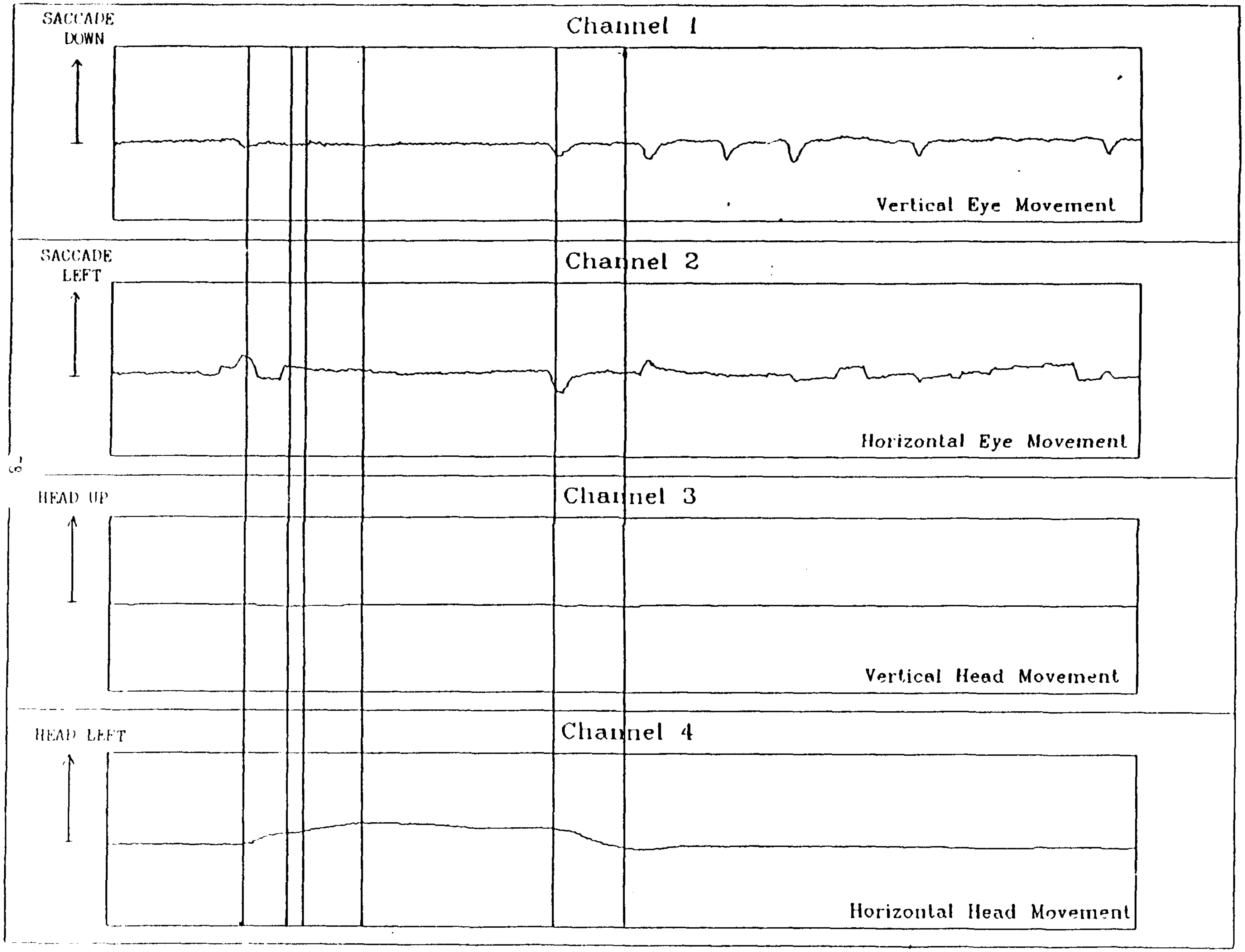
SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23B



SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23C



SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23D

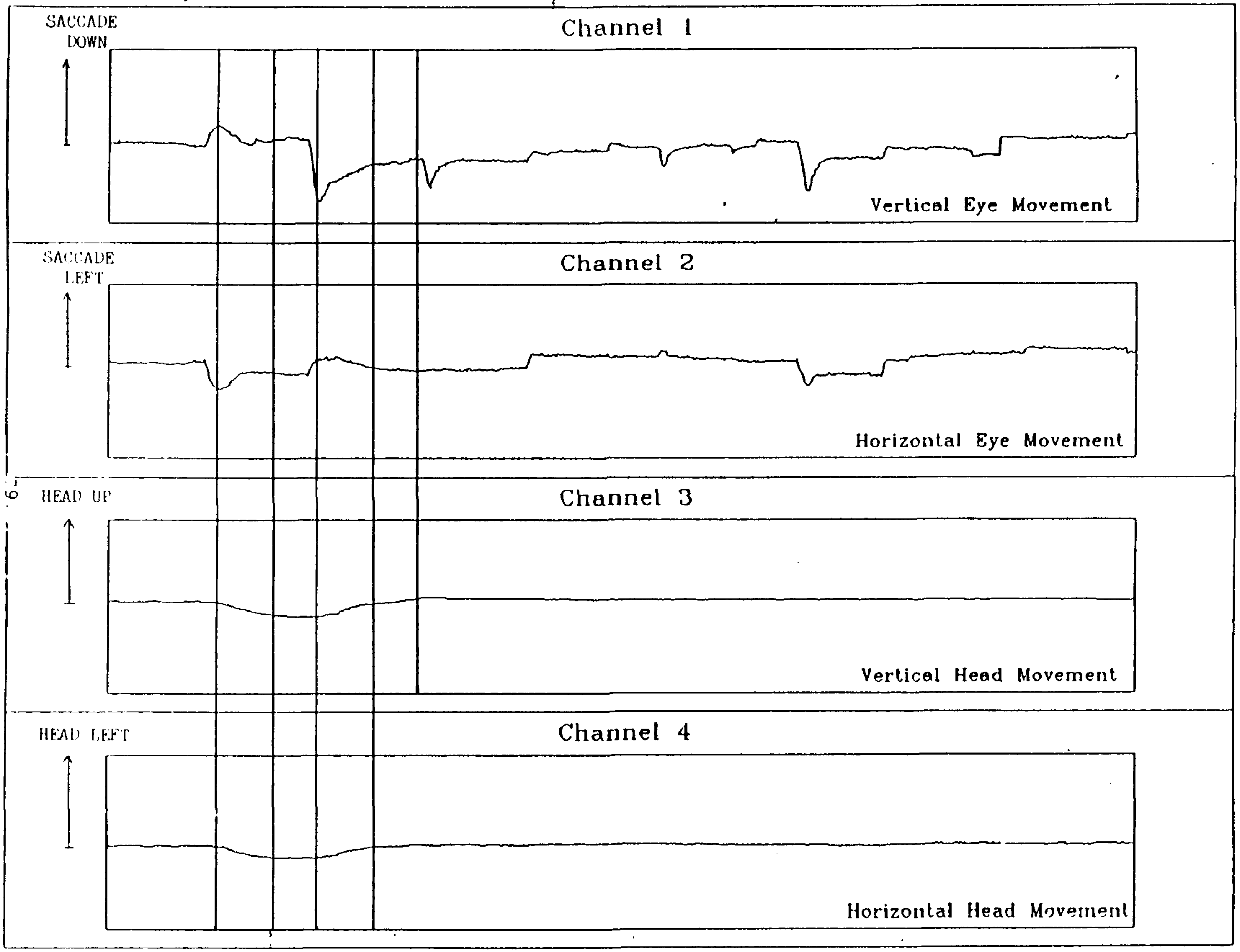

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23F

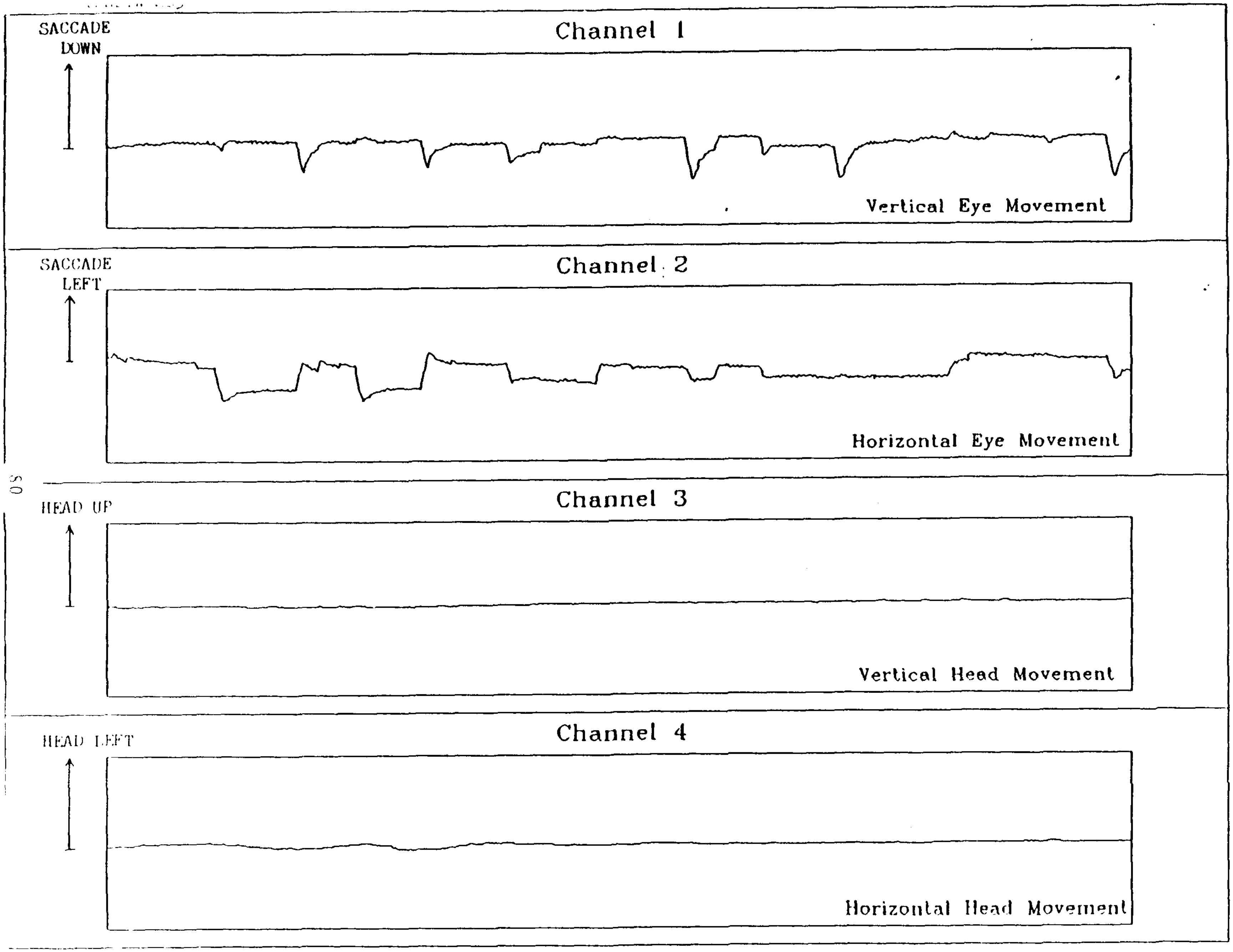
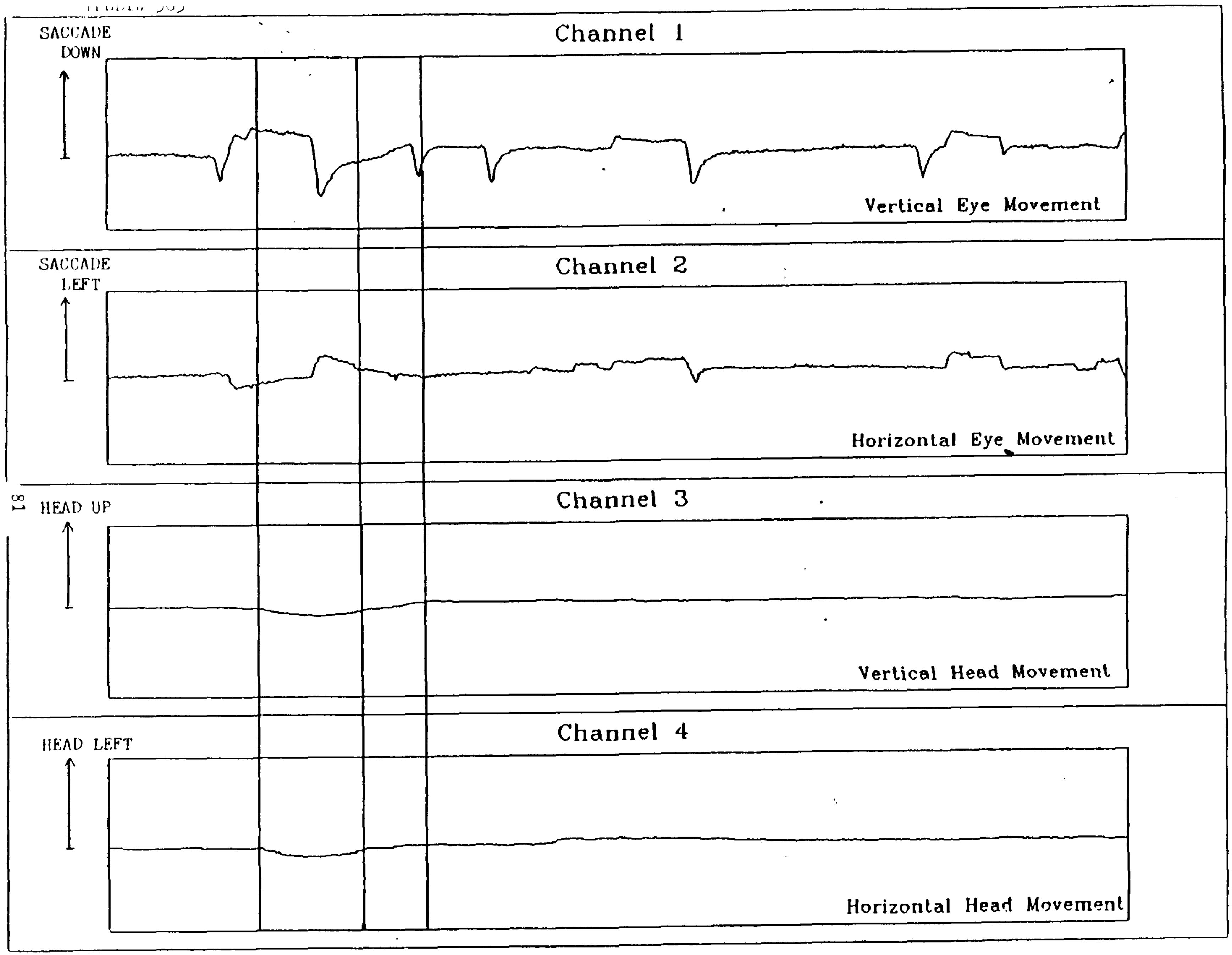

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23F



Channel 1
SACCADE DOWN
Vertical Eye Movement
Channel 2
SACCADE LEFT
Horizontal Eye Movement
Channel 3
HEAD UP
Vertical Head Movement
Channel 4
HEAD LEFT
Horizontal Head Movement

FIGURE 23G

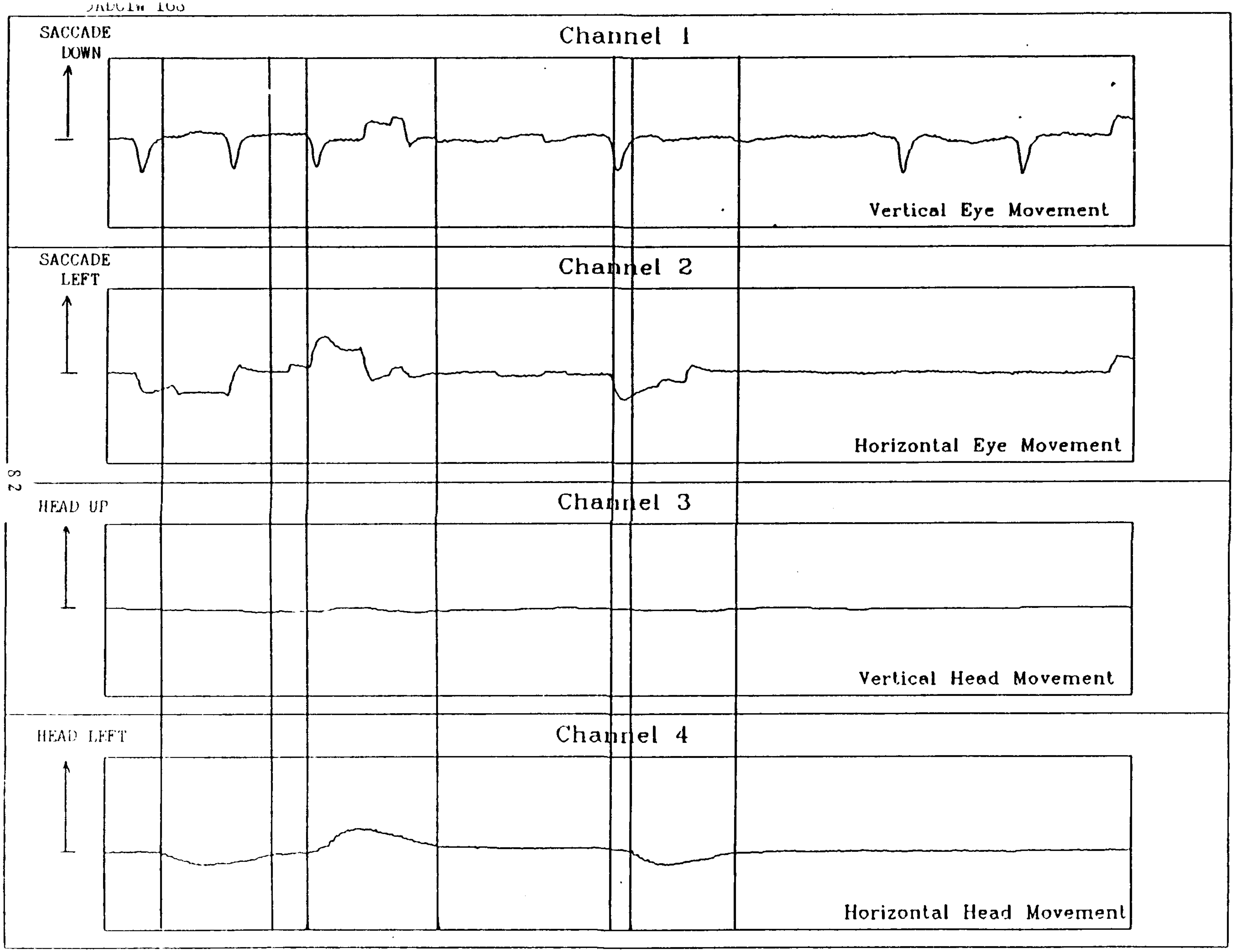

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23H

SADCIW 269

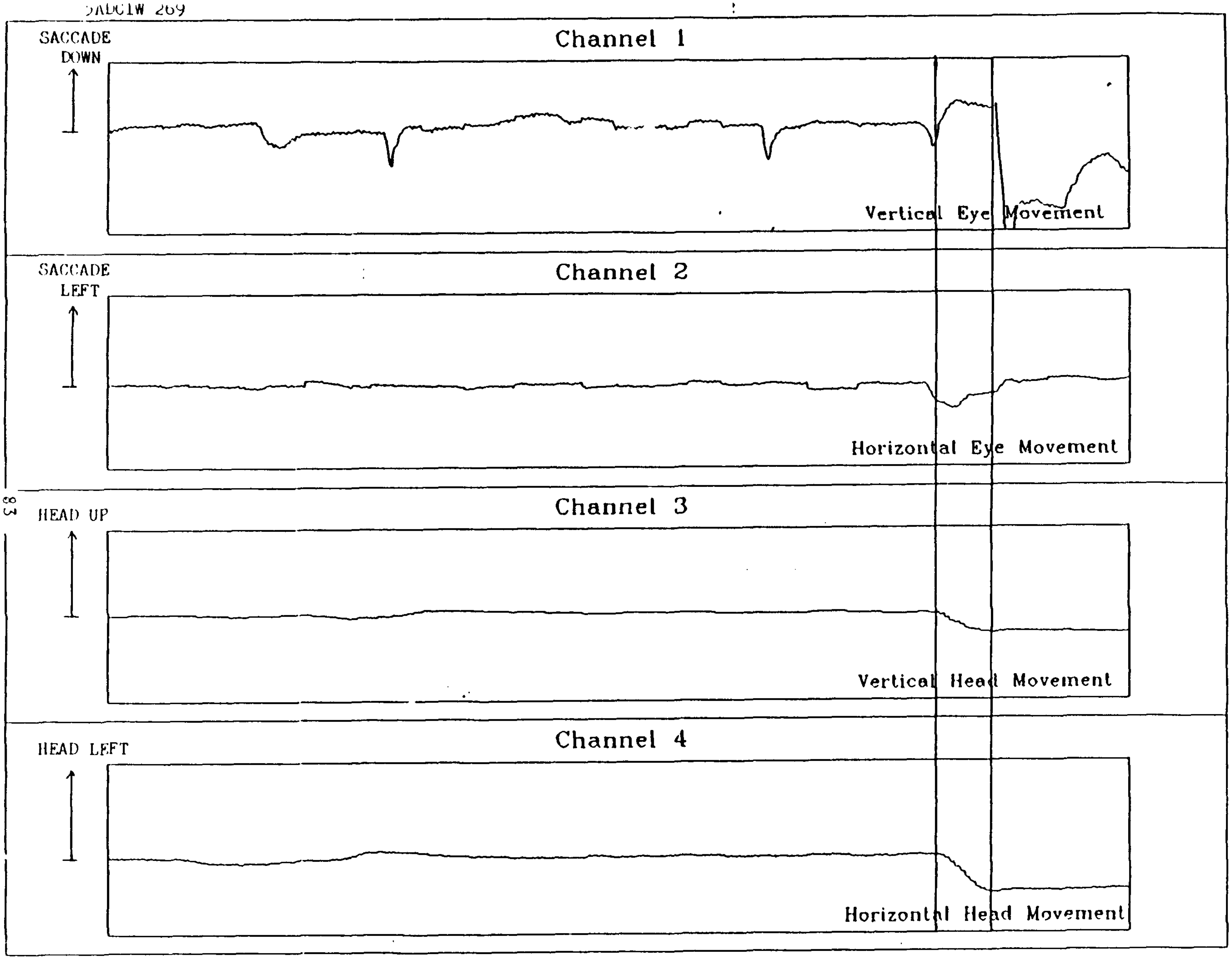
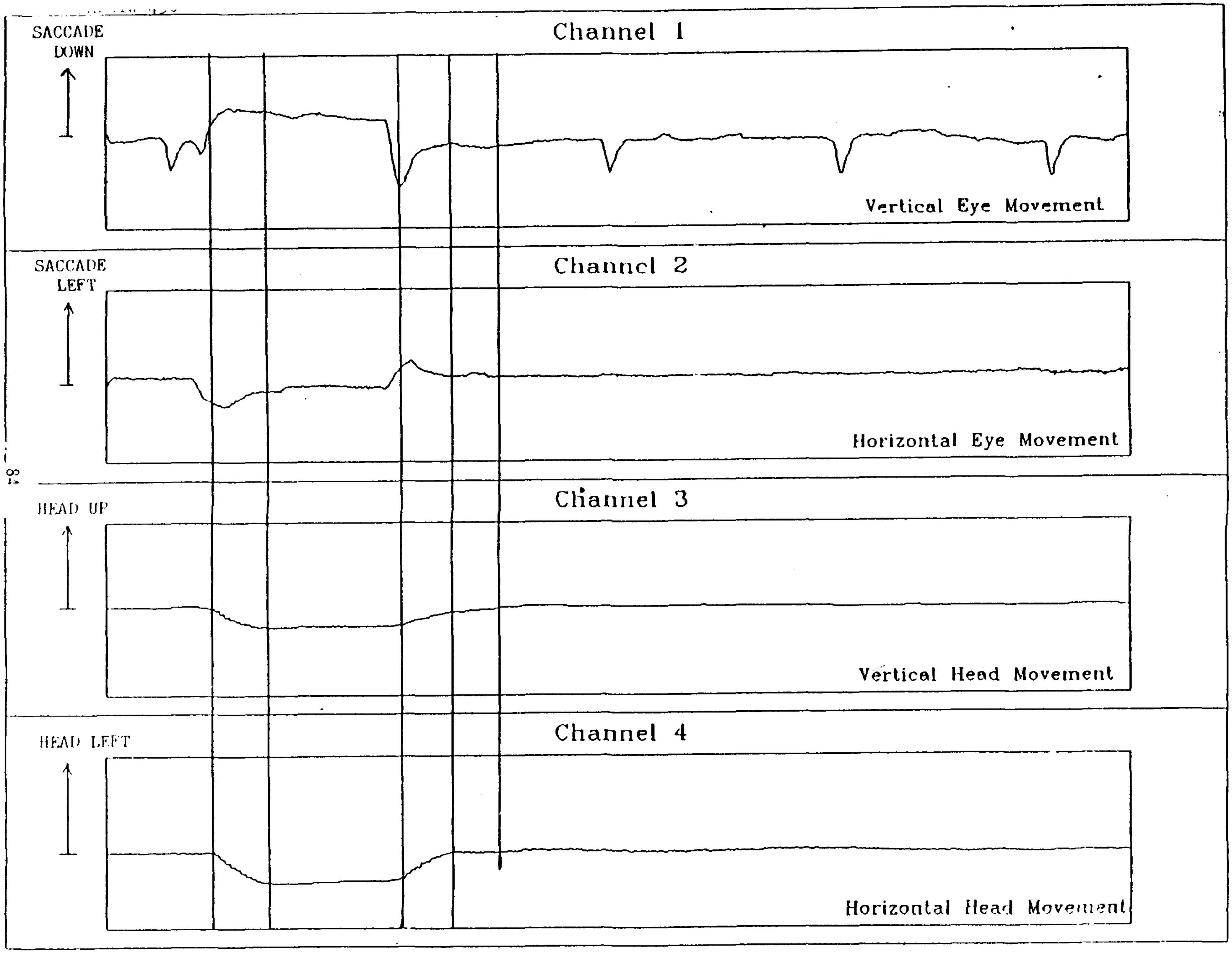


FIGURE 23I



SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23J

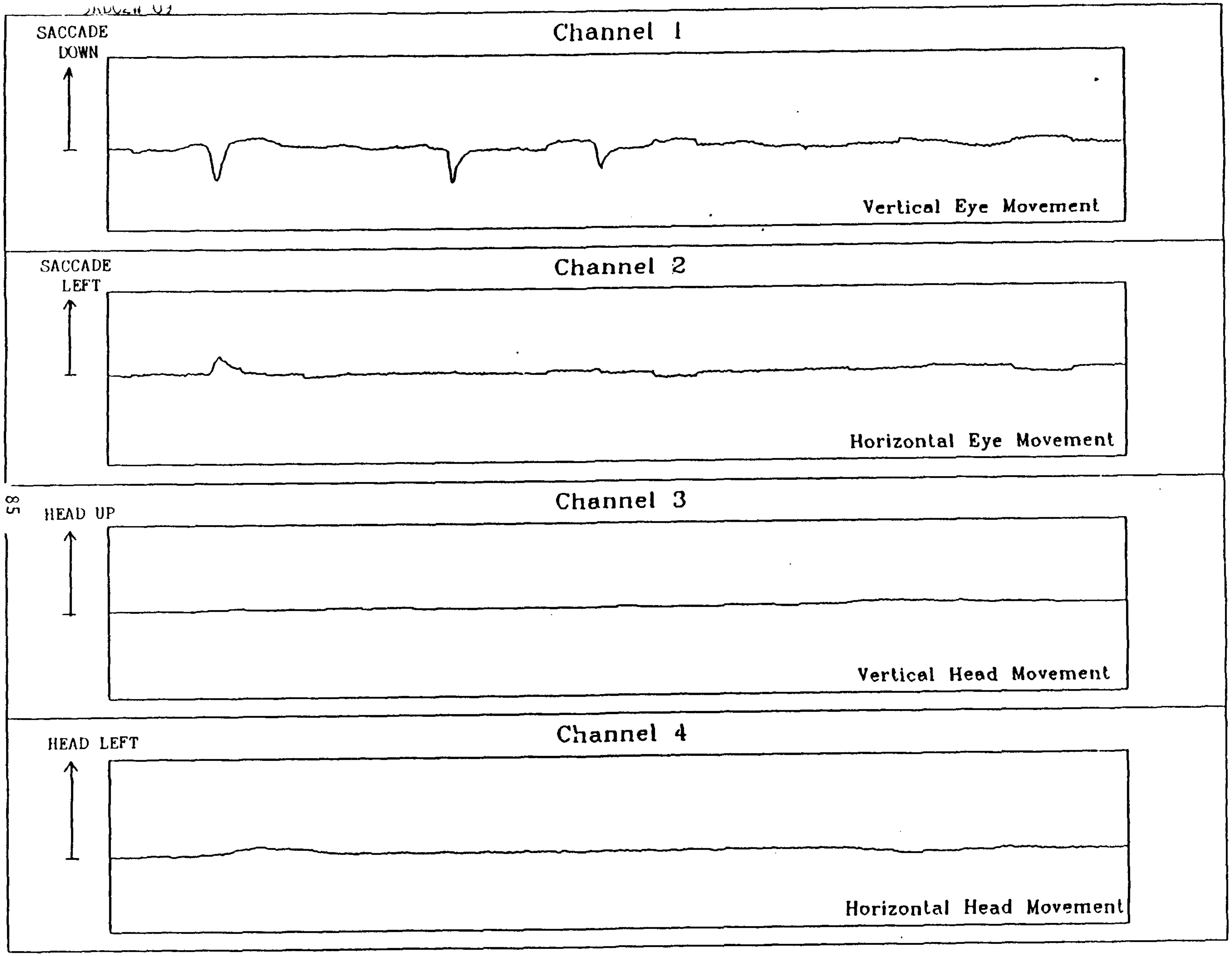

SACCADE
DOWN
Channel 1
Vertical Eye Movement
SACCADE
LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23K

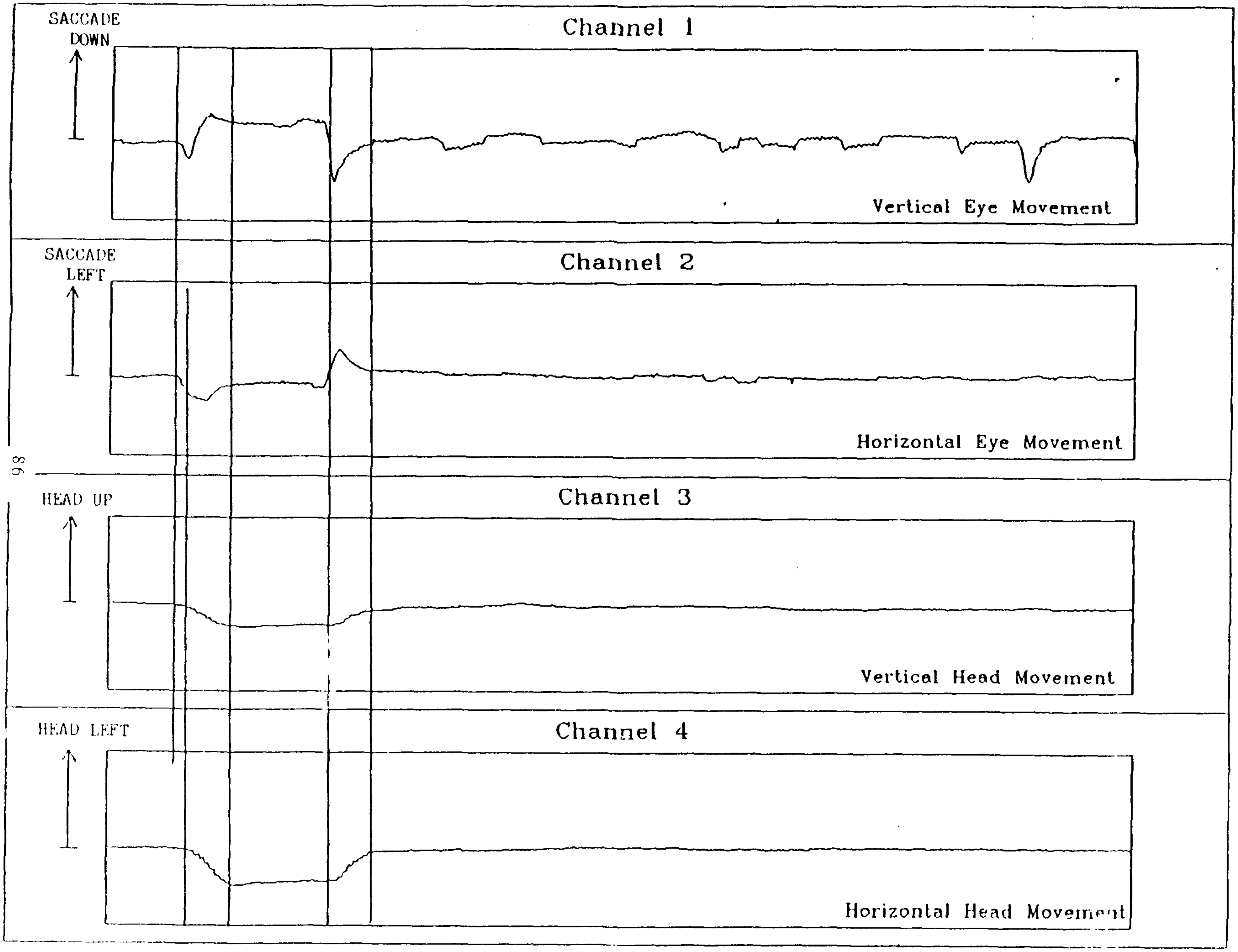

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23L

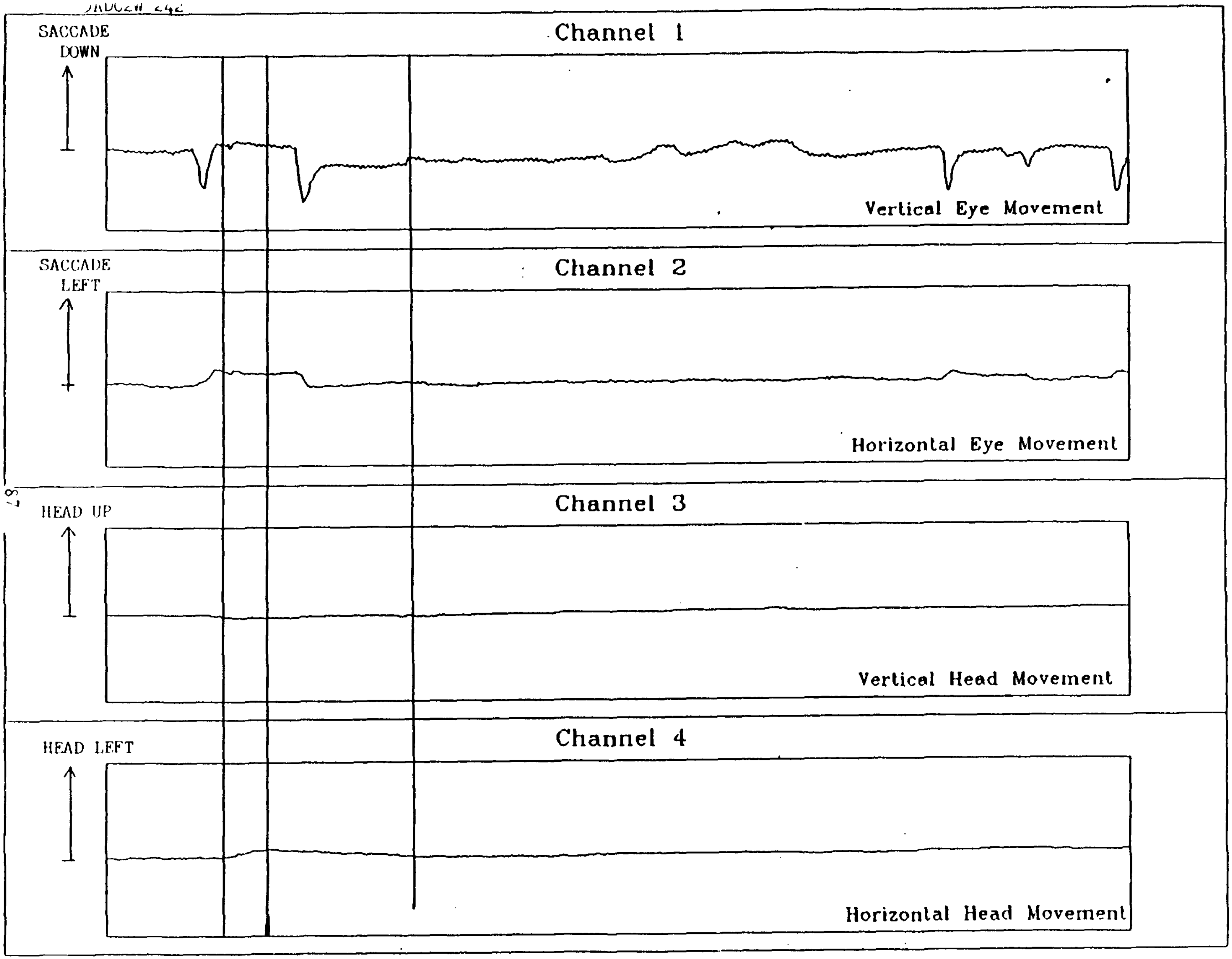

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 2.3M

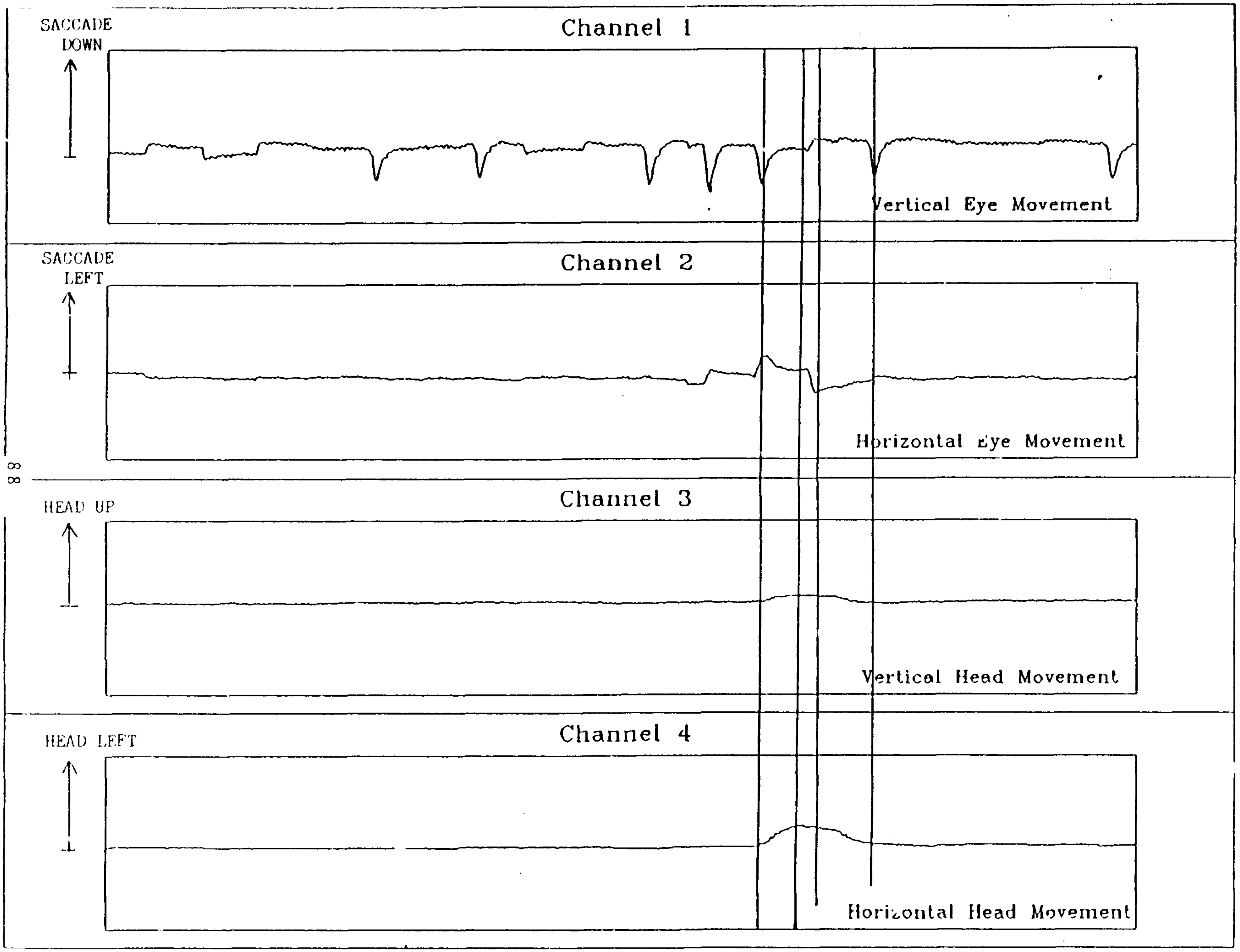

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 2 3N

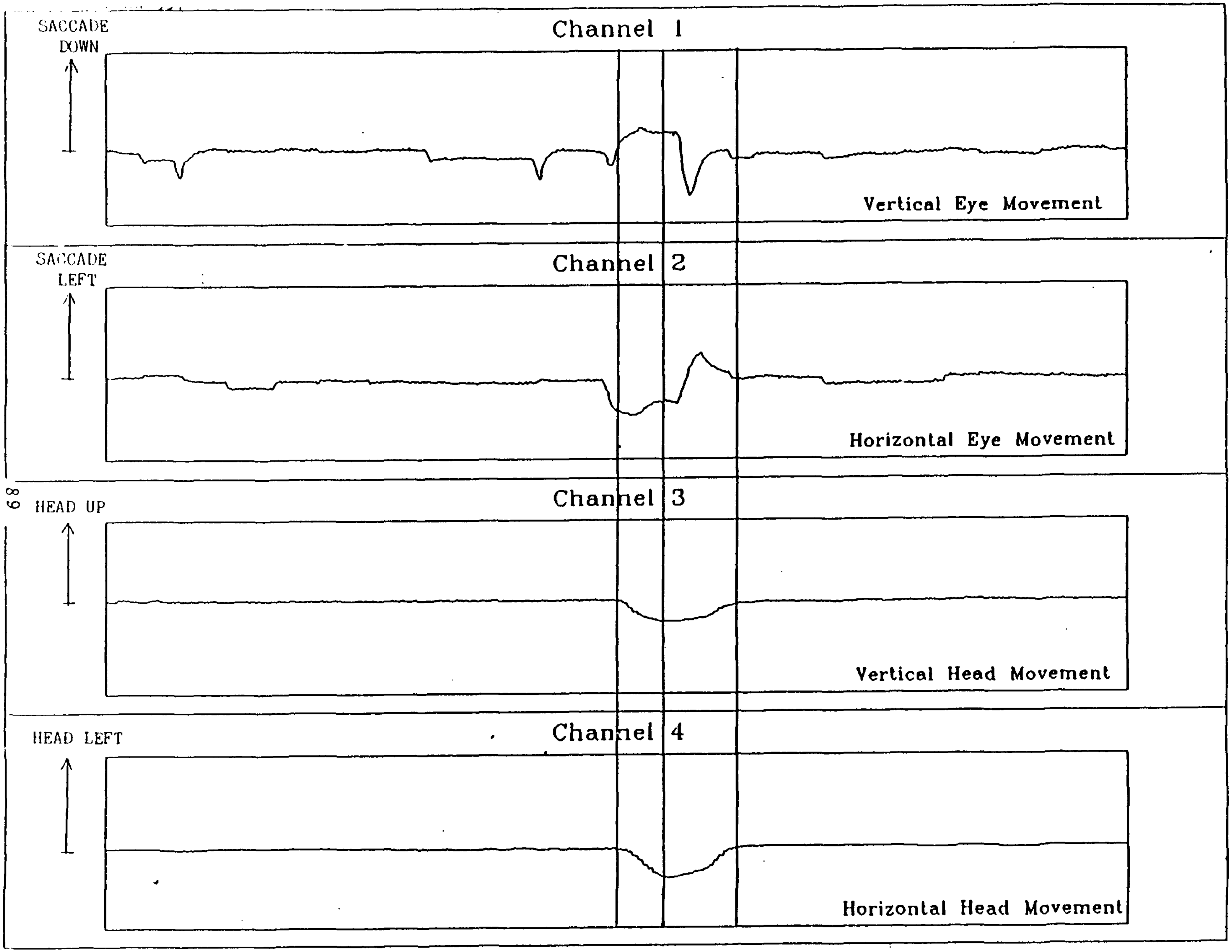
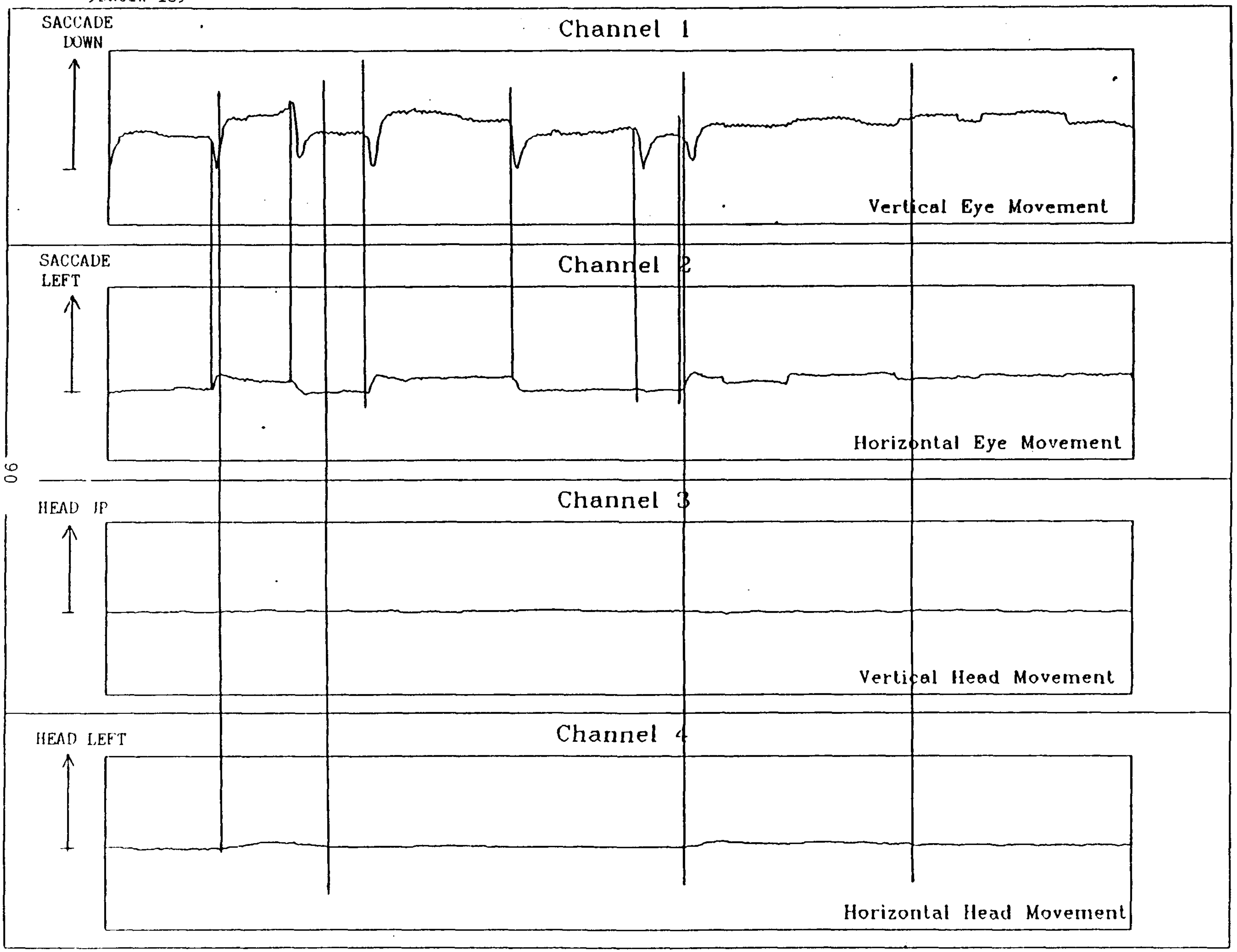
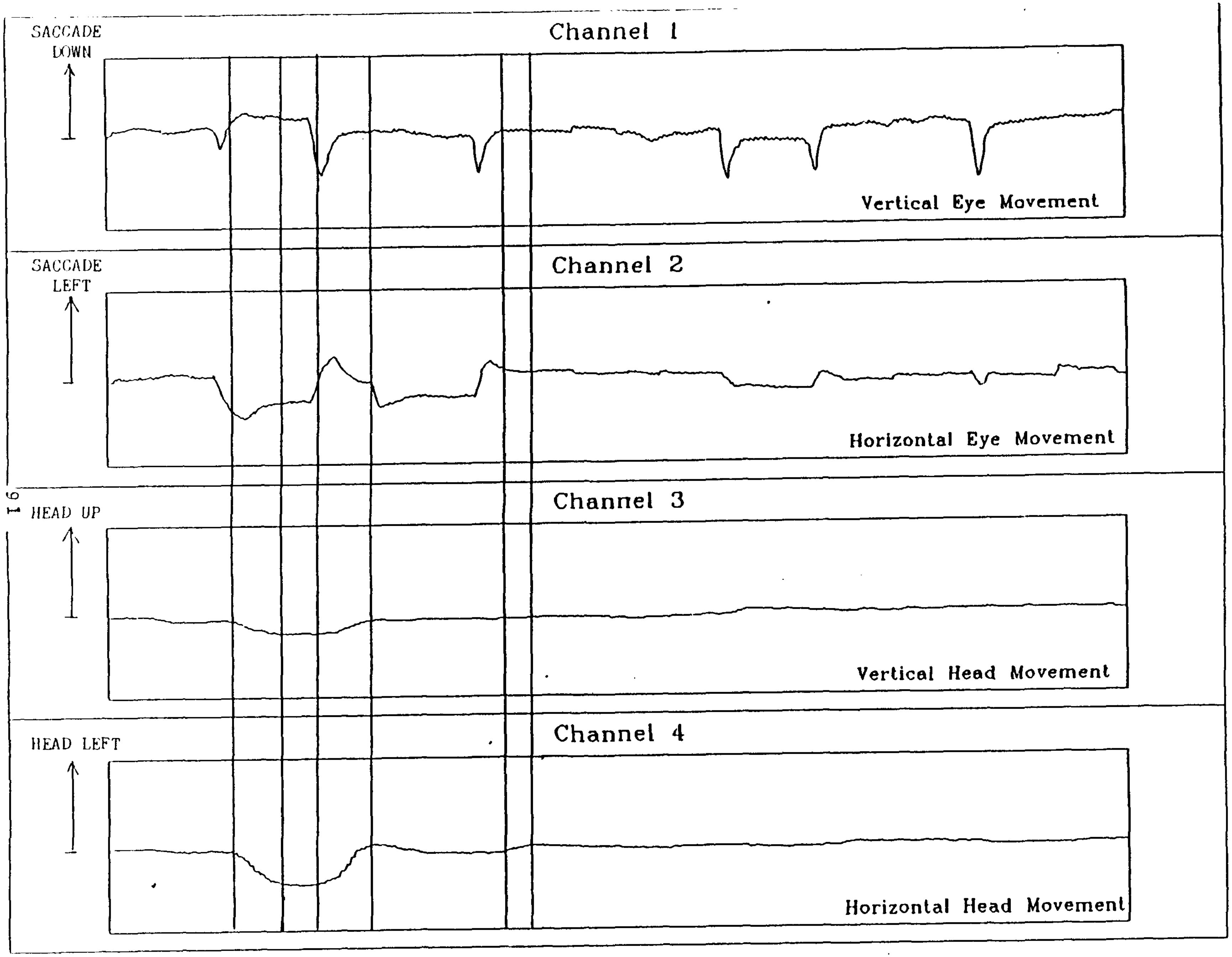

Channel 1
SACCADE DOWN
Vertical Eye Movement
Channel 2
SACCADE LEFT
Horizontal Eye Movement
Channel 3
HEAD UP
Vertical Head Movement
Channel 4
HEAD LEFT
Horizontal Head Movement

FIGURE 230



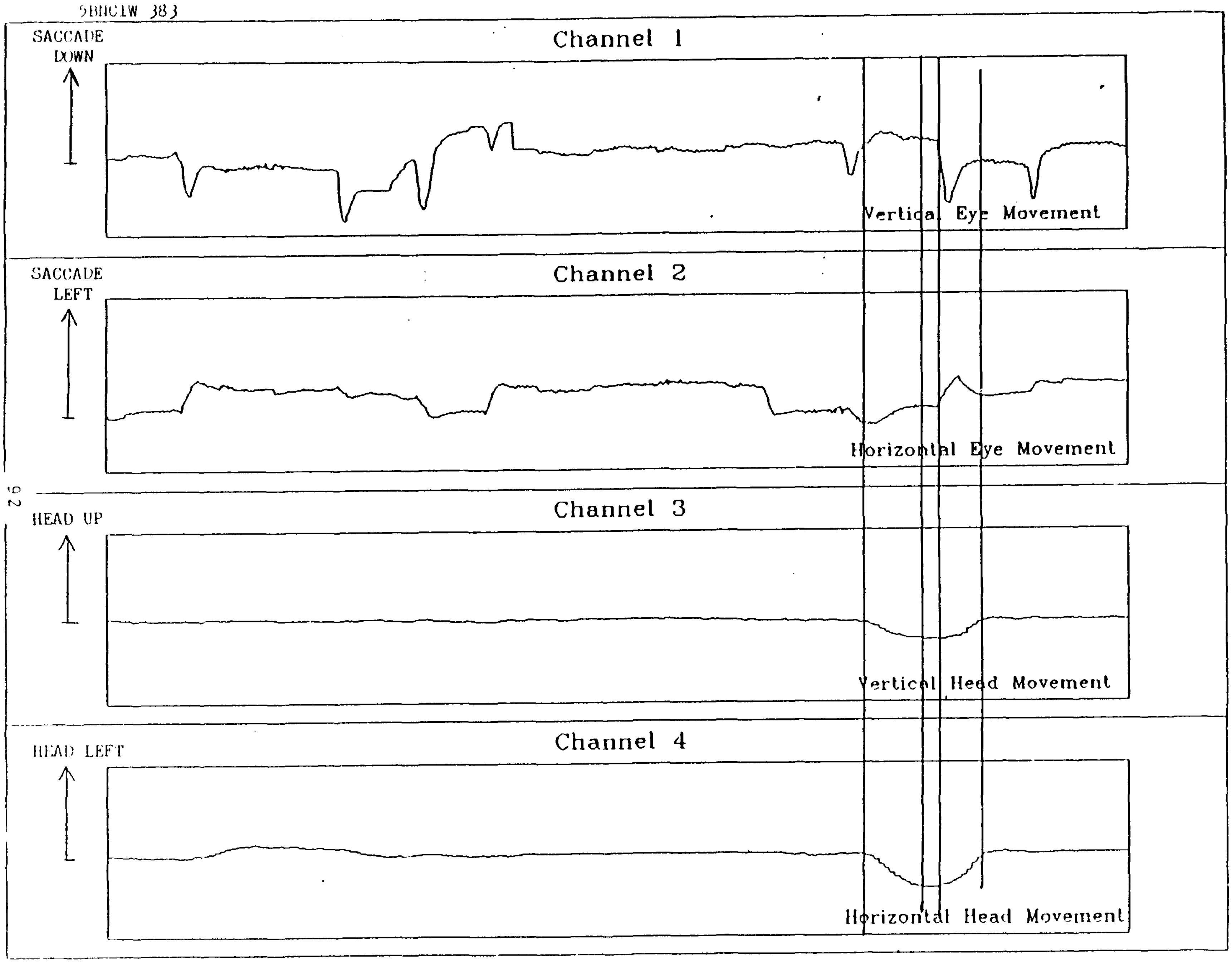
SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23P



Channel 1
SACCADE DOWN
Vertical Eye Movement
Channel 2
SACCADE LEFT
Horizontal Eye Movement
Channel 3
HEAD UP
Vertical Head Movement
Channel 4
HEAD LEFT
Horizontal Head Movement

FIGURE 23Q



5BHC1W 383
SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23R

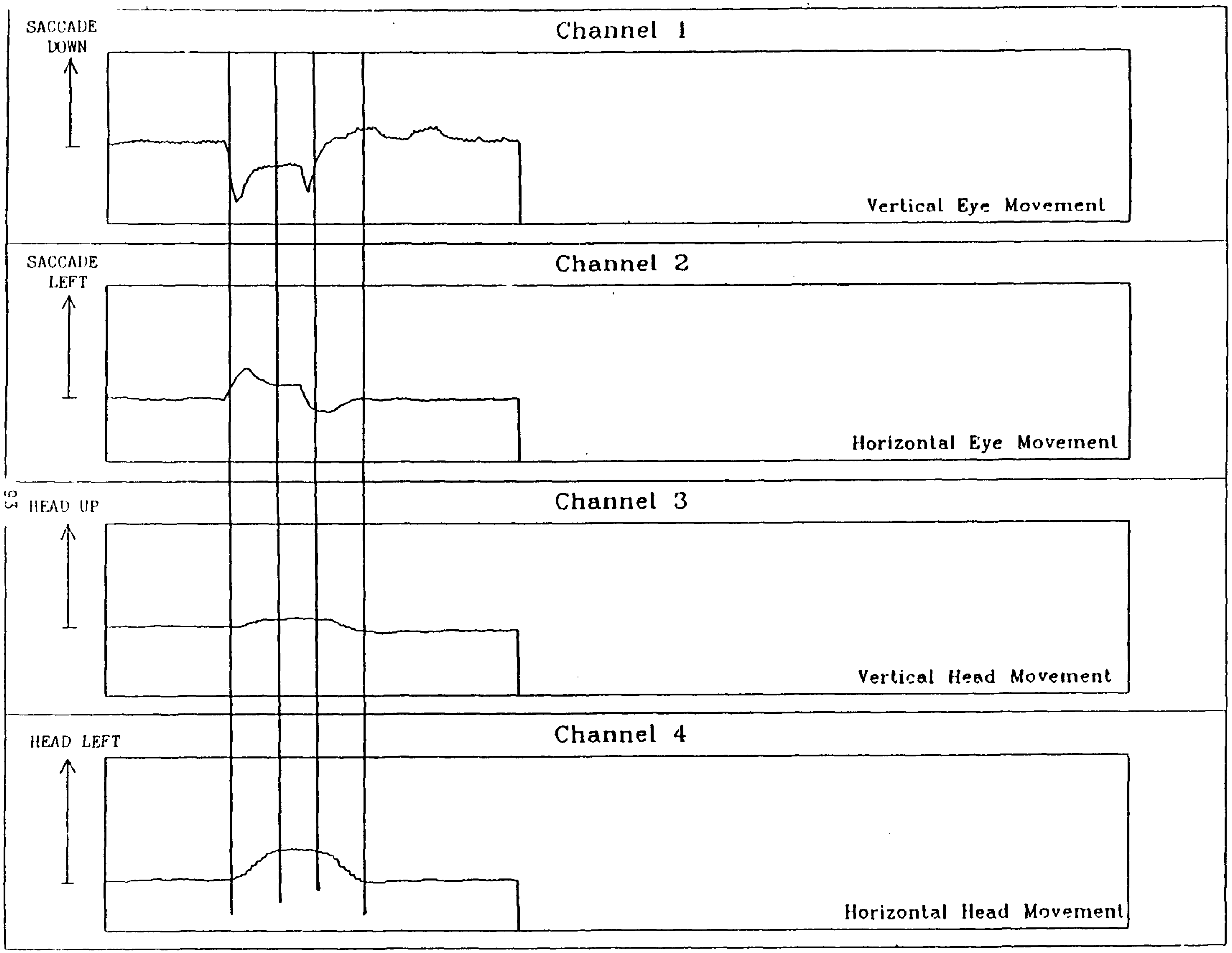

SACCADE DOWN
Channel 1
Vertical Eye Movement
SACCADE LEFT
Channel 2
Horizontal Eye Movement
HEAD UP
Channel 3
Vertical Head Movement
HEAD LEFT
Channel 4
Horizontal Head Movement

FIGURE 23S

gain settings were used for all data sets.

2.2 Sampling, Filtering, and Digitizing Procedures

All data were sampled at 10 msec intervals and were low-pass (analog) filtered (100 Hz cutoff). No other filtering was done. It should be pointed out that during recording, the head movement signals are digitized at 50 msec sampling intervals. The data were then D/A converted off-line and recorded on analog tape, together with the EOG data. The fact that the head movements were initially sampled at 50 msec intervals is readily apparent in those tracings with large amplitude head movements in that the intervals between successive steps are approximately 50 msec in duration.

2.3 Display Format

In all displays, Channel 1 contains vertical EOG. Blinks are identified as downward going. From an EOG standpoint, an upward eye movement is the same as the lid moving down over the eye (a blink). Thus, upward saccades, as well as blinks, are translated into downward deflections. Channel 2 presents horizontal EOG data; left is up and right is down. Channels 3 and 4 present vertical and horizontal head movements. In the vertical channel, up is up and down is down. In the horizontal plane, head left is an upward deflection; head right is downward. It should be noted that we have only abstracted part of the data available from the Polhemus head tracker. Based on our observations of the pilots, we assume that these two dimensions captured the majority of head movement shifts.

2.4 Interpretation of Displays

The data in Figure 23A were abstracted from subject #1's refuel flight D, run under HMD conditions. They depict the period preceding the sighting of the tanker (about 30 seconds before "tally-ho"). The vertical lines drawn on the tracings index the onset and termination of head movements. It should be pointed out that when we speak of eye movements, the reference is a change of eye position with respect to the head.

Approximately 1.6 seconds into the display, the pilot looks downward (channel 1) and returns the eye to the initial position a half second later (ch 1). About 120 ms after the initiation of the eye movement, a downward head movement (ch 3) is initiated. The return head movement (ch 3) is made after the eye returns (ch 1) to the original fixation point. Approximately 8.2 seconds into the display, he looks both downward (ch 1) and to the left (ch 2). His head movements down (ch 3) and to the left (ch 4) again lag the onset of the eye movements. We can also see that the head movements are accompanied by compensating eye movements indicating the following sequence: his eyes saccade down and to the left; his eyes remain fixated on the same point and his head then follows the eye movement (note the compensating deflections in the eye movement channels); the amplitude of the head movement is less than that of the eye movement, a fact that is suggested by the raised channel 1 and 2 baselines; finally, since no further movements occur in this block, the pilot is in position in which his eyes are down and to the left, fixated on the peripheral stimulus, and his head is turned slightly in the same direction.

This pilot does a lot of blinking (which are numbered in tracing 23A). We find that a blink is initiated approximately 300 ms before the head starts to move downward. The total duration of the blink is 200 ms, with eye position higher in the visual field following the blink than at blink initiation. There is a brief fixation pause (100 ms) followed by the large amplitude downward saccade, descibed above. Saccade duration is approximately 120 ms. A compensatory eye movement in the direction opposite the head movement is initiated concurrently with the head movement. Approximately 150 msec after head movement initiation, we see a small amplitude saccade in the direction of the initial large saccade, followed by stabilization of the eye before the head movement is completed. Approximately 500 msec following major saccade termination, we observed a vertical saccade coupled with an eye blink. The saccade/blink is initiated approximately 100 msec before the head starts its return movement. The head movement is initiated at the trough of the eye blink. Eye position stabilizes approximately 200 msec before the head movement terminates. There are no horizontal eye movements associated with this vertical head and eye movement pattern.

An entire sequence of eye and head movements downward and to the left, and return to the central position, is depicted in the next figure. The return of the head to the central location has the vertical component initiated approximately 150 msec before the horizontal component, with the two terminating concurrently. Again, the vertical head movement is initiated during a blink/saccade, with the eye stabilized in the vertical plane at the point the head movement starts. A second blink occurs concurrently with head movement termin[illegible]. In the horizontal plane, a saccade/glissade is initi[illegible]ced concurrently with blink initiation in the vertical plane. This eye movement is terminated with vertical head movement initiation. A "compensatory" slow drift toward the left accompanies the head movement to the right, but, again, is completed some 150 ms before completion of the head movement.

What inferences, which may be tested on other data, are we willing to make from these two figures? In Figure 23B, we see that the complex head movement has blinks associated with termination, but not the initiation, of the gaze shift. Based on other data, we are willing to make the inference that acquisition of the peripheral information was important to the pilot. A blink in association with gaze shift initiation slows down the speed at which such information becomes accessible to the viewer. A second inference to be drawn from Figure 23B is that head movements for picking up peripheral information are most likely to occur where gaze on the peripheral information is long. "Long," in the present context, is about 1.5 seconds. Approximately 800 ms following completion of the gaze return, we see an eye movement which, in the horizontal plane, is approximately the same amplitude as the eye movement associated with the gaze shift involving a head movement. The fixation duration here is approximately 200 ms.

It should be noted that this saccade is made during the terminal portion of an eye blink, with a vertical eye position shift also occurring during the blink. One might infer here that acquisition of the peripheral information may have served only as a check on the information acquired during the gaze shift (involving a head movement), since the saccade is made during a blink. Also note that the horizontal saccade made during a blink has the same velocity characteristics (slope) as the return saccade made in the absence of a blink.

Figure 23C depicts an example where, instead of compensatory eye movements, one sees a head movement that overshoots the target and slowly drifts backward to a position that is then maintained for more than four seconds before the head returns to a central position. Other examples of complex head movements can be seen in Figures 23E, G, and H). Notice in Figure 23C that again, the horizontal eye movement, as well as the initiation of the compensatory eye movement, precedes the initiation of the head movement, and that the compensatory eye movement terminates long before the head movement is completed (350 msec). Also, note that the return head movement, although considerably larger in amplitude than that seen in Figure 23B, does not have the "characteristic" saccade, glissade, compensatory eye movement seen with the previous head movements. This attests to the impression of the richness of combinations of head and eye movements that may occur. The first seven figures (23A to 23G) depict data for subject 1; the remaining ones are for subject 5, who also does a lot of blinking.

2.5 Conclusions

The eye movement patterns associated with head movements recorded in flight simulation are somewhat at variance with the literature. A number of reasons for the discrepancies can be identified. We believe the most important are, first, that the eye and head movements made in the present context were self-initiated, rather than triggered by stimuli presented by an experimenter. Second, the head movements in the simulator generally involved both horizontal and vertical components, but, in any case, were not predictable, while those described in the literature deal predominantly with eye movements to acquire stimuli presented in one plane only, generally horizontal. A third reason may be the complexity of the display. In laboratory studies, gaze has to be shifted from one location to another with no information available between. The simulator environment is considerably richer; information is presented between primary locations that may be of incidental utility to the pilot and he can acquire this information while gaze is shifting between locations. This type of information acquisition pattern has not been studied in the laboratory, to the best of our knowledge. A fourth reason may be equipment artifact. However, although we had no way to determine the lag in the movement recording produced by the A/D and subsequent D/A conversions, our best guess is that this lag is of the order of milliseconds, at most.

In all data depicted, head movements lagged eye movement initiations, in both the vertical and horizontal planes, by somewhere between 100 and 200 ms. This is considerably longer than the 50 msec lag that we and others (Bizzi, 1974) have observed in both monkey and man, where task demands are relatively simple. There are others, of course, who have reported latencies in the range obtained here (Bartz, 1966; Calhoun et al., 1986; Gresty, 1974; Mourant & Grimson, 1977). This leads us to believe that these lags are not equipment artifacts, but valid measures.

The most interesting (and difficult to rationalize) result is that the so-called compensatory eye movements (compensating for head movements) are frequently found to be initiated in anticipation of head movement, and terminate before the head finishes moving. As such, therefore, they must be centrally controlled, rather than simply mechanical reactions to head movements under conditions where the viewer wishes to maintain the peripheral object in foveal vision.

Both the glissade at the end of a saccade and the compensatory eye movements are relatively slow movements, and therefore do not suffer from the visual suppression associated with the more rapid saccadic eye movement. Thus, to the extent that the viewer can utilize these types of eye movements instead of saccades, he can "see" environmental stimuli earlier than would be true under saccade only conditions.

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H. GENERAL SUMMARY

1.0 Photic Stimulation

Reasonable evidence for photic driving could be found in the simulator data. Although some evidence suggested that the degree of photic driving was a function of "momentary" workload, this finding was not consistently manifested in the details of the data. Reasons for this are proposed and generally indicate the necessity for research that is more tightly controlled than is possible in the simulator. This research (described in the report) would be designed to determine the effect of a variety of parameters on the magnitude of steady-state EPs, such as:

a) Intensity (and its relation to critical flicker frequency)
b) Consistent and quantifiable workloads
c) Workload quality
d) Procedures to maintain the constancy of the visual input to subjects whose gaze is shifting.

2.0 Blinks and Saccades

Differences between the HMD and noHMD conditions were obtained, suggestive of higher workload under NoHMD conditions. These differences were found for pilot activity associated with waypoints in the ingress flight condition, and for all segments of tanker rendezvous. No differences were found during threat avoidance and post-threat conditions.

This HMD/NoHMD difference was reflected most strongly in the degree of conjoint occurrence of eye blinks and saccades. Earlier work suggested that the incidence of concurrent blinks and saccades increases under conditions of high visual task demand. Since the present data indicate that the blink/saccade coincidence is greater under the noHMD condition, we infer that use of the helmet display reduces visual task demands. A second measure (and only slightly less discriminative of workload demands) was saccade frequency; more visual searching is done under the noHMD than the HMD condition. These results suggest:

a) Pilots rapidly learn to make use of the information presented on the HMD in favor of obtaining such information from the instrument panel, but that
b) They do not use the added time available, as a consequence of this more efficient information abstracting capability, in scanning their environment (presuming such scanning is desirable).
c) Specific training or further practice may be necessary to assure better utilization of "released time."

3.0 Head Movements and Saccades

Patterns of head and eye movements observed in the flight simulator are considerably at variance with most data collected under more highly controlled laboratory conditions, i.e., our ability to generalize information collected under laboratory conditions may be poorer than expected. Some discrepancies between simulator and laboratory data are:

a) The timing between saccade and head movement initiation was consistently longer under flight simulation than laboratory conditions.
b) Eye movement patterns were more complex than seen under laboratory conditions.
c) Compensatory eye movements frequently terminated before the end of a head movement.

A number of reasons for the lack of generalizability can be hypothesized. Most important among these are:

a) In the simulator, gaze shifts are self-directed, while in the laboratory, they are initiated at experimenter-controlled time points.
b) Information content of the "display" in the simulator is considerably richer and variable (dynamic) than in the laboratory.

These results suggest that the dynamic relationship between eye and head movement is more likely to be a function of central information processing demands than of more purely perceptual variables.

I. APPENDIX A

B-1B REPRESENTATION

1.0 Description of the F-15E Cockpit

An F-15E simulator will be used for the B-1B HMD evaluation. Some changes have been made to its software so as to imitate the B-1. The cockpit layout, shown in Figure A-1, has not been changed. The following description includes only those displays and instruments that will be used during the test.

The F-15E has a "glass cockpit." It features three cathode ray tubes (CRT), multipurpose displays (MPD), an integrated comm/nav control panel, which we refer to as the "Up Front Control" (UFC), and a wide field of view (WFOV) head up display (HUD). This cockpit is designed for maximum flexibility; it is possible to place a variety of displays on each of the MPDs, including radar imagery, infrared imagery, weapon video, and systems status. Only the left and right MPDs will be used for the B-1 test.

The HUD will be present but will not be used to display information. A set of "round dial" backup flight instruments are located on the left subpanel below the left MPD. These instruments will be the only source of calibrated airspeed and mean sea level (MSL) altitude when the HMD is off.

On the right subpanel, below the MPD, there is an integrated engine display and an integrated fuel display. The RPM indications on the engine display will be functional during the B-1 test, but will not be calibrated to match B-1 engine settings. They are intended merely to provide some indication of thrust setting to the pilot.

The F-15E stick grip and throttle grips, shown in Figure A-2, incorporate numerous switches. We refer to these as "HOTAS" switches (Hands On Throttle And Stick). In the F-15, they are used to control aircraft sensors and weapons functions. Only five of these switches will be active during the B-1 test. Their use is explained below.

2.0 Genair B-1B Flight Model

Genair is a generic flight model enabling the modeling of the handling characteristics of any aircraft. In this program, it is used to simulate the B-1's flight handling, and has been judged by two B-1 pilots as being very faithful in this respect for the two mission segments to be used: tanker rendezvous and low level threat penetration.

3.0 Vision Restriction

The F-15E has a two-seat, tandem mounted cockpit whereas the

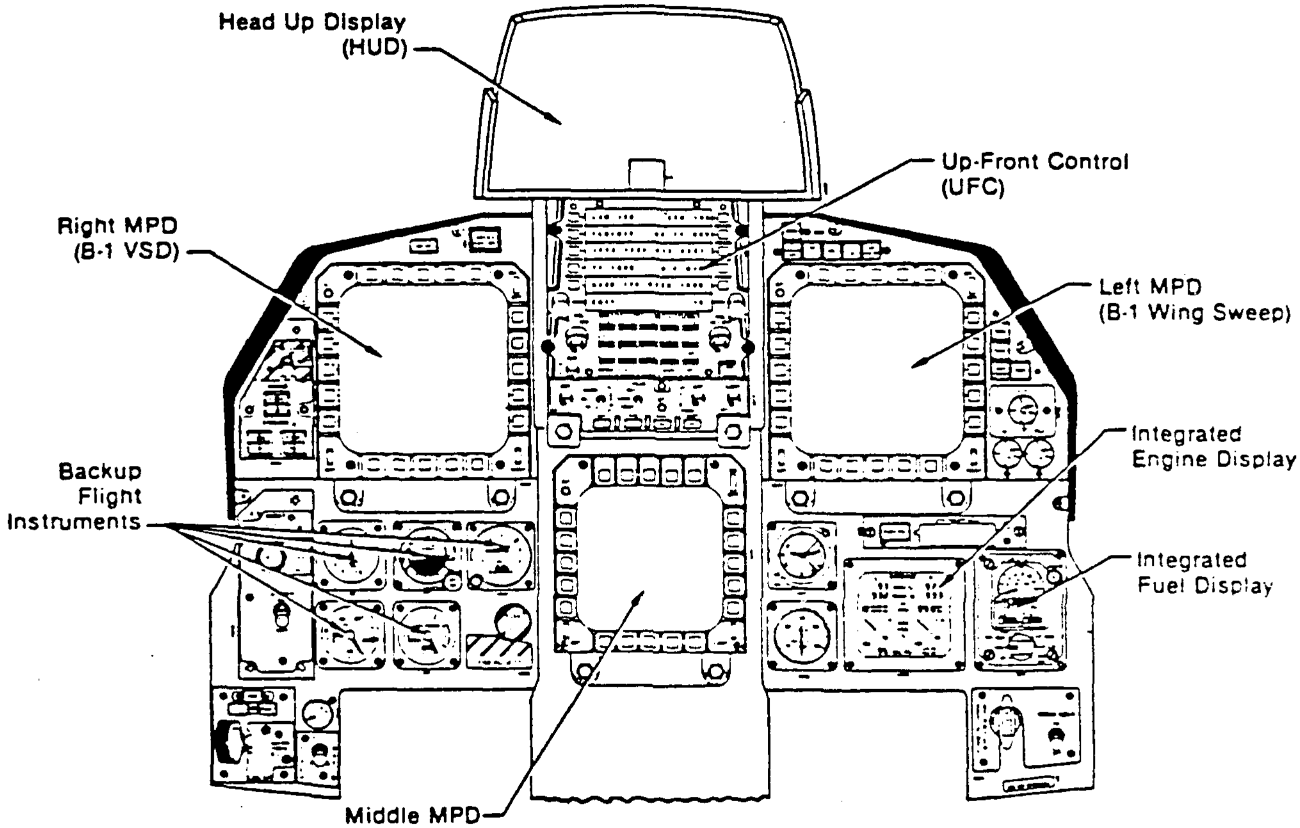

FIGURE A-1. F-15E COCKPIT

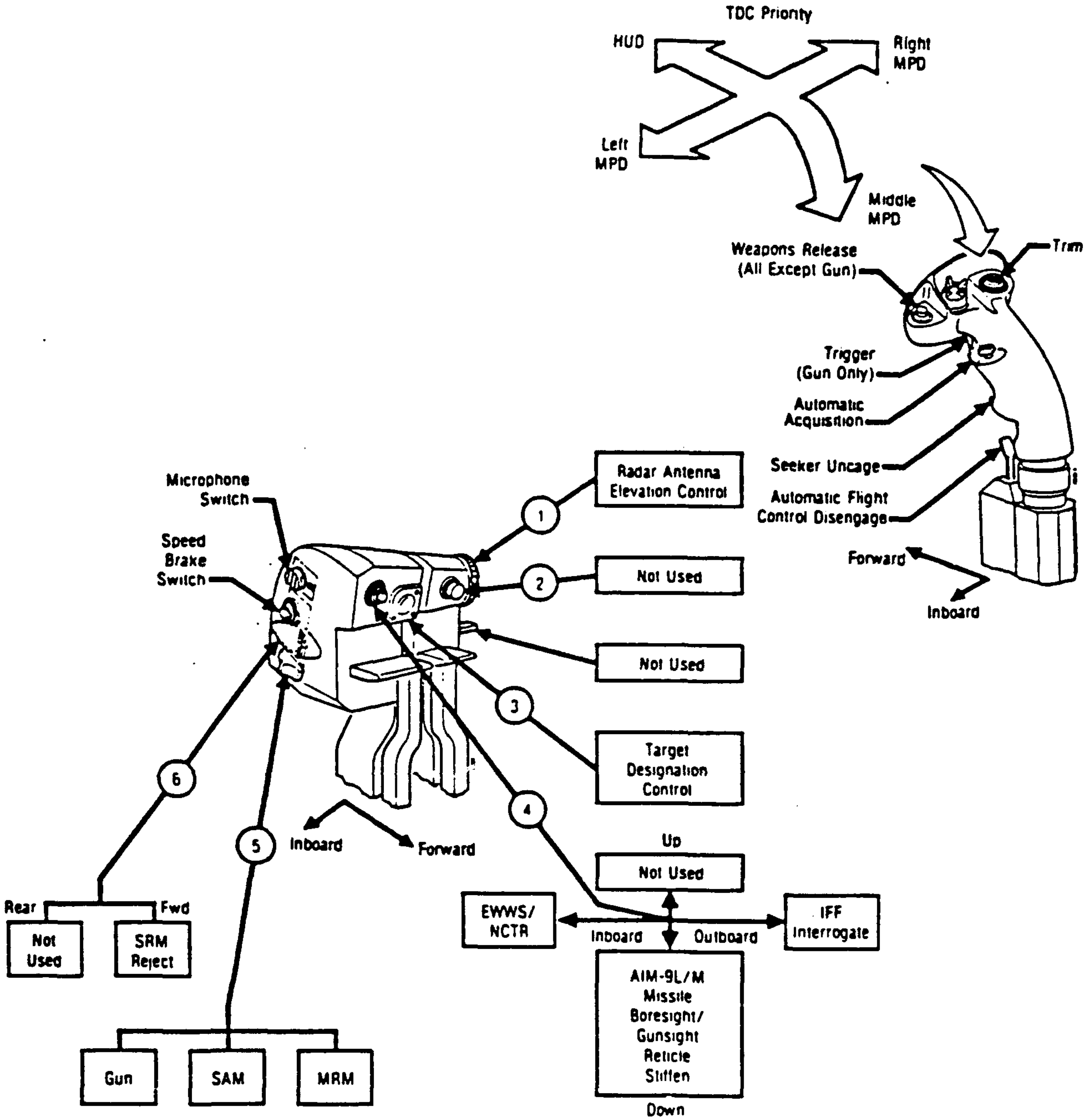

FIGURE A-2. F-15E STICK GRIP AND THROTTLE CONTROLS

B-1B has a side-by-side cockpit that restricts the pilot's vision somewhat. To perform a reasonable evaluation of the HMD, when used in this type of aircraft, the B-1 window configuration has been emulated by placing a foam core shell (weighing ten pounds) over the F-15 cockpit (Figure A-3). It is not fastened to the cockpit; it merely rests on the cockpit canopy sills. This shell closely matches the aircraft on the left side and directly in front of the pilot but the simulator dimensions preclude adding a right side to the cockpit. As a partial solution, the right wall of the shell has been designed to appear like a B-1 cockpit to the pilot when he looks cross-cockpit from his normal position. The pilot will defeat the intent of this device if he moves his head excessively to the right and will be instructed to avoid this movement.

4.0 Cockpit Displays

The left and right MPDs will be used during the HMD evaluation. The pilot should not need to turn these on, but may want to adjust display brightness and/or constrast. The controls for this are shown in Figure A-4, and will be demonstrated during the training sessions. They are as follows:

4.1 B-1 VSD Display - The left MPD will be used to provide a simulated B-1 VSD, shown in Figure A-5. This should behave similarly to the aircraft VSD, but a few comments are in order to describe how it has been programmed:

4.1.1. Range Indicator - The range numeric in the lower left corner will indicate range to the tanker during the tanker rendezvous missions, and range to the next waypoint during low level penetration missions.

4.1.2. Ground Speed Indicator - This numeric always shows ground speed.

4.1.3. Altitude - MSL altitude will be displayed at all times in the upper right corner of the VSD. This will be provided only for altitudes below 5000 ft.

4.1.4 Steering Cross - During tanker rendezvous missions, the steering cross will be caged at the center of the aircraft symbol. During low level penetration, the steering cross will provide command steering to the centerline of each leg of the planned route.

4.2 Wing Sweep Indicator - The right MPD will be used to provide a Wing Sweep Indicator, shown in Figure A-6. The top of the scale represents the forward sweep limit of 15°; the bottom represents the aft limit of 67.5°. Each tick mark on the scale represents a 10° increment. The

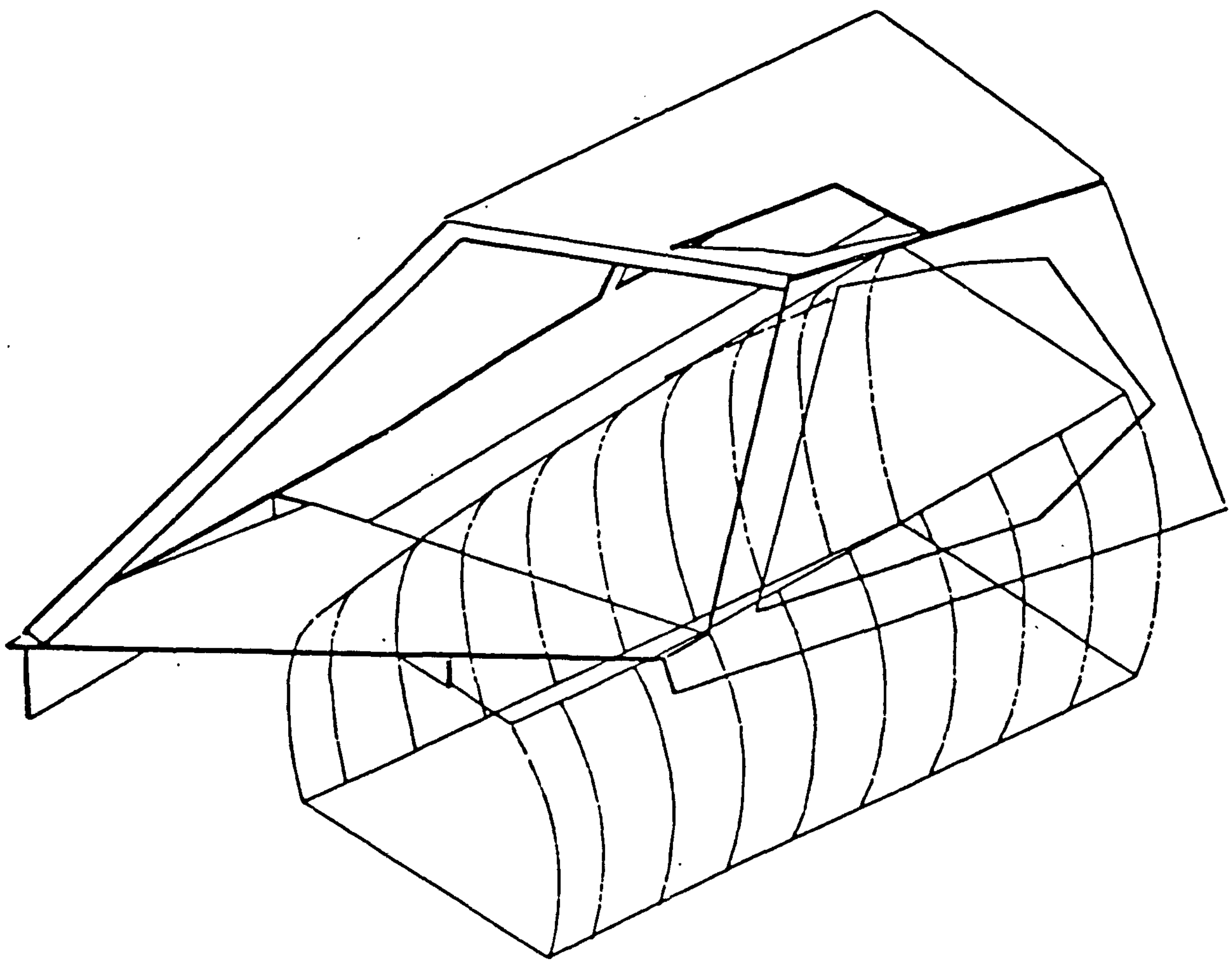

FIGURE A-3. B-1 VISION RESTRICTION SHELL

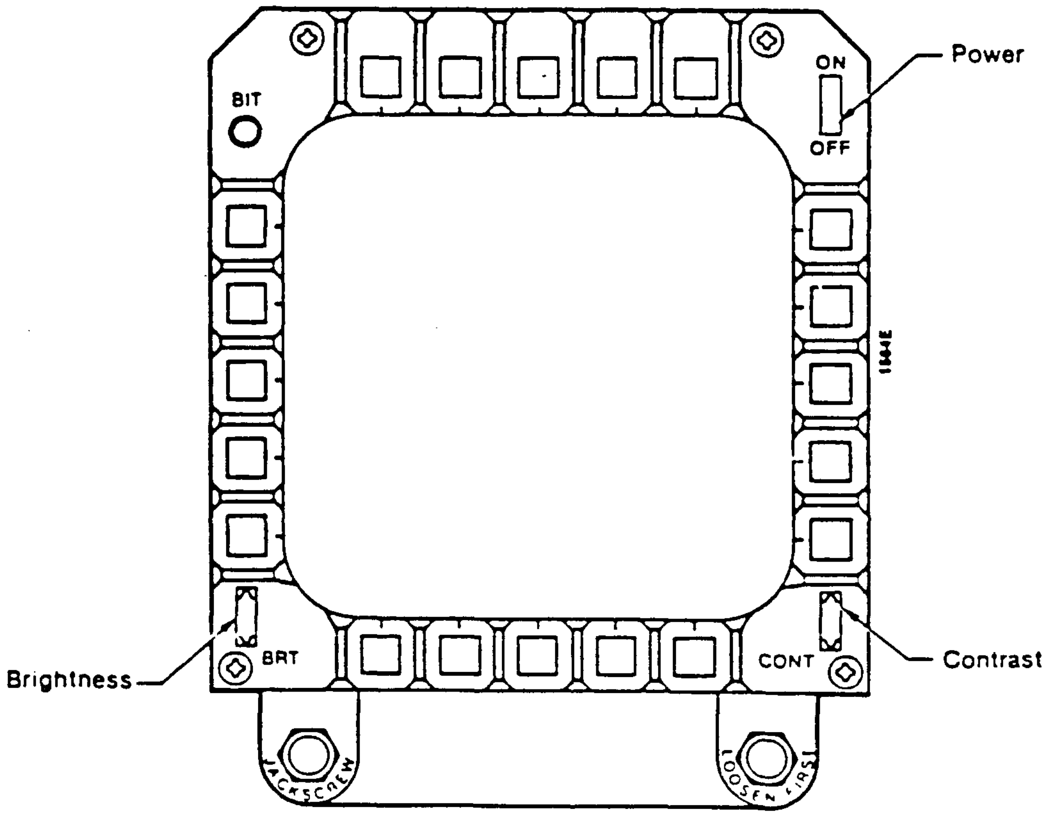

FIGURE A-4. MULTIPURPOSE DISPLAY CONTROLS

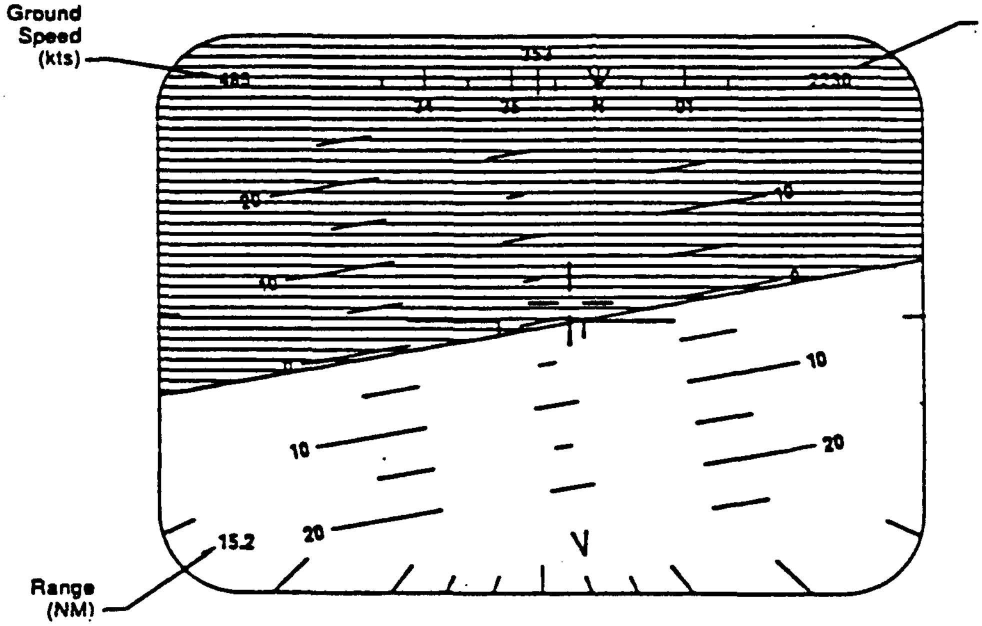

FIGURE A-5. B-1 SIMULATOR VSD FORMAT

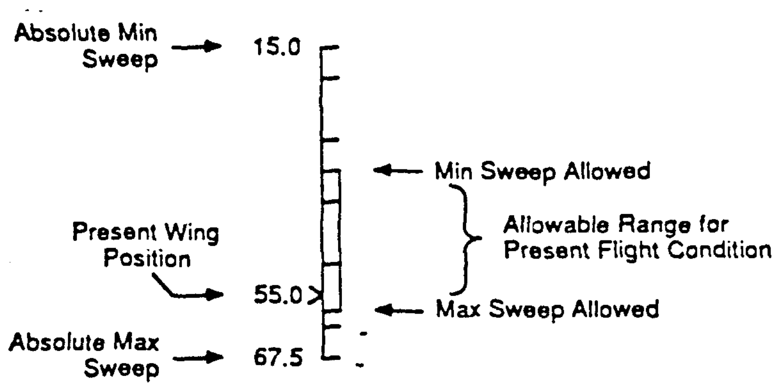

FIGURE A-6. SIMULATION WING SWEEP INDICATOR carat and number on the left of the scale indicates present wing position.

The bar on the right of the scale indicates the forward and aft wing limits based on current flight conditions. This is depicted in Figure A-7.

The allowable range bar is dynamic and is continually repositioned to depict the present wing position limits as a function of flight conditions. If changing flight conditions result in the present position being out of limits, the wings move as necessary to remain at either the forward or aft limit (depending on which is critical). The wings will move to the position selected by the pilot whenever this position is within the allowable range. The pilot selects wing position with the wing sweep switch on the throttle.

B. B-1 HELMET MOUNTED DISPLAY

1.0 Kaiser Agile Eye System

The Agile Eye helmet mounted display (HMD) system is manufactured by Kaiser Electronics. A prototype version of this system will be used for this test. Because this is a prototype, some aspects of the system are less than ideal.

The HMD system is composed of three major subsystems: the helmet itself, the head tracker and the display system. These are illustrated in Figure A-8 and described briefly below.

1.1 Agile Eye Helmet - The Agile Eye helmet was designed as a new flight helmet with the HMD integrated into it from the beginning. The new design improved three basic characteristics of the present flight helmet. The amount of aerodynamic lift at high speed is cut in half. The weight was redistributed so that the overall CG of this helmet is closer to the natural CG of the human head than present helmets. The total weight, with tracker and display elements, is one-half pound lighter. This is done by using new components and Kevlar for the shell, which provides the strength required for a flight helmet, but greatly reduces the weight.

1.2 Head Tracker - The Agile Eye system employs an electromagnetic tracking system manufactured by Polhemus Navigation Sciences. A source, positioned above the pilot's head, radiates three orthogonal magnetic signals. In the simulator, the source is mounted on an arm above and attached to the ejection seat. In an aircraft, it can be mounted anywhere, as long as it has a clear line of sight to the helmet.

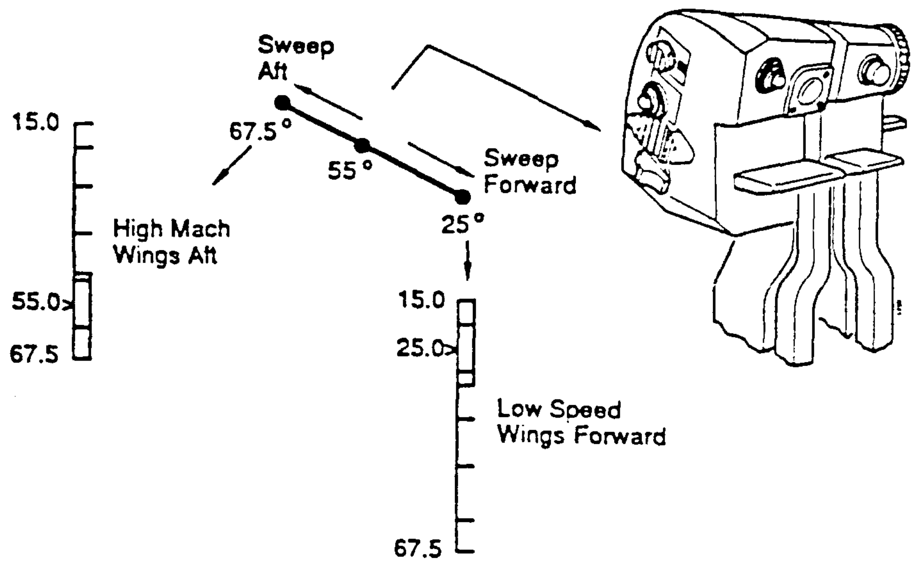

FIGURE A-7. B-1 WING SWEEP

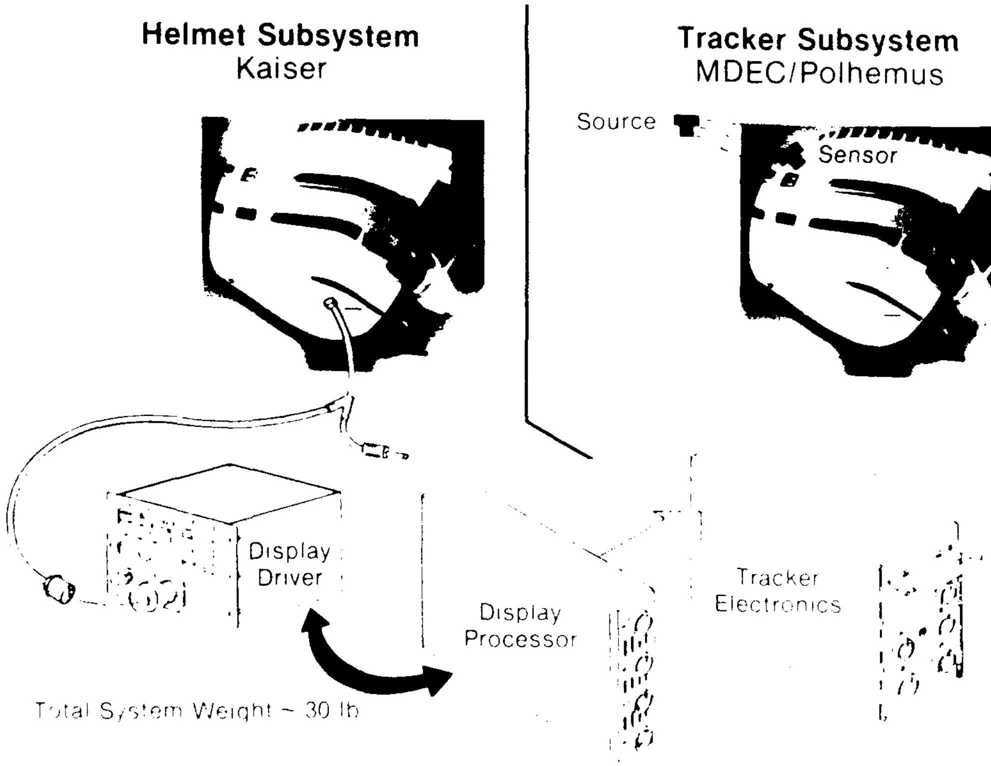

FIGURE A-8. "AGILE EYE" HELMET SYSTEM

The receiver is mounted on the inside and at the top of the Agile Eye helmet. Changes in the orientation of the helmet relative to the source cause changes in the received signal. By comparing the two, helmet position and orientation are determined. From these, line of sight (LOS) angles are computed. The display is then tailored for the LOS. Accuracy is 1/2 degree, which is adequate for most flight operations.

1.3 Helmet Display System - The display is provided by a half-inch diameter cathode ray tube (CRT) mounted inside the helmet on the right side. The CRT image is carried to the helmet visor optically, using fiber optics and mirrors. The visor is the final optical element and acts as the combining glass for the display, superimposing the display elements on the outside visual scene. This system produces a display that has a 12° field of view (FOV), which can be positioned at any LOS that the pilot can achieve through head movements.

The video signal for the display is generated by a digital graphics processor. This signal is transmitted to the helmet at a low voltage level so that no spark is produced by quick disconnect of the necessary electrical lines. A high voltage power supply is located within the helmet, and converts the input video signal to the voltage levels necessary to drive the helmet CRT.

2.0 HMD Controls

2.1 HMD Control Panel - The control panel for the HMD is shown in Figure A-9. The only control necessary to activate on this panel is the HMD brightness control, which should be adjusted as desired at the start of each session. This panel is located on the left console.

2.2 HOTAS Switches - Two HOTAS switches are used to operate the HMD. Use of the boresight switch, located on the stick, is covered in the next paragraph. The blanking switch, located on the left throttle, is used to temporarily turn the display off by holding the switch depressed. The location of these switches is shown in Figure A-10.

2.3 Helmet Boresight Procedure - The position and orientation of the helmet can be determined very precisely. However, a known reference must first be supplied to the system. This is accomplished by boresighting the helmet. We have provided a very simple mechanism for accomplishing this. At the start of each session, simulation engineers will place the Simulator in "Reset" mode. To "boresight the helmet," the Boresight Switch on the stick grip is pressed and held. A box with a center cross will be displayed on both the F-15 HUD and the Agile Eye HMD, as

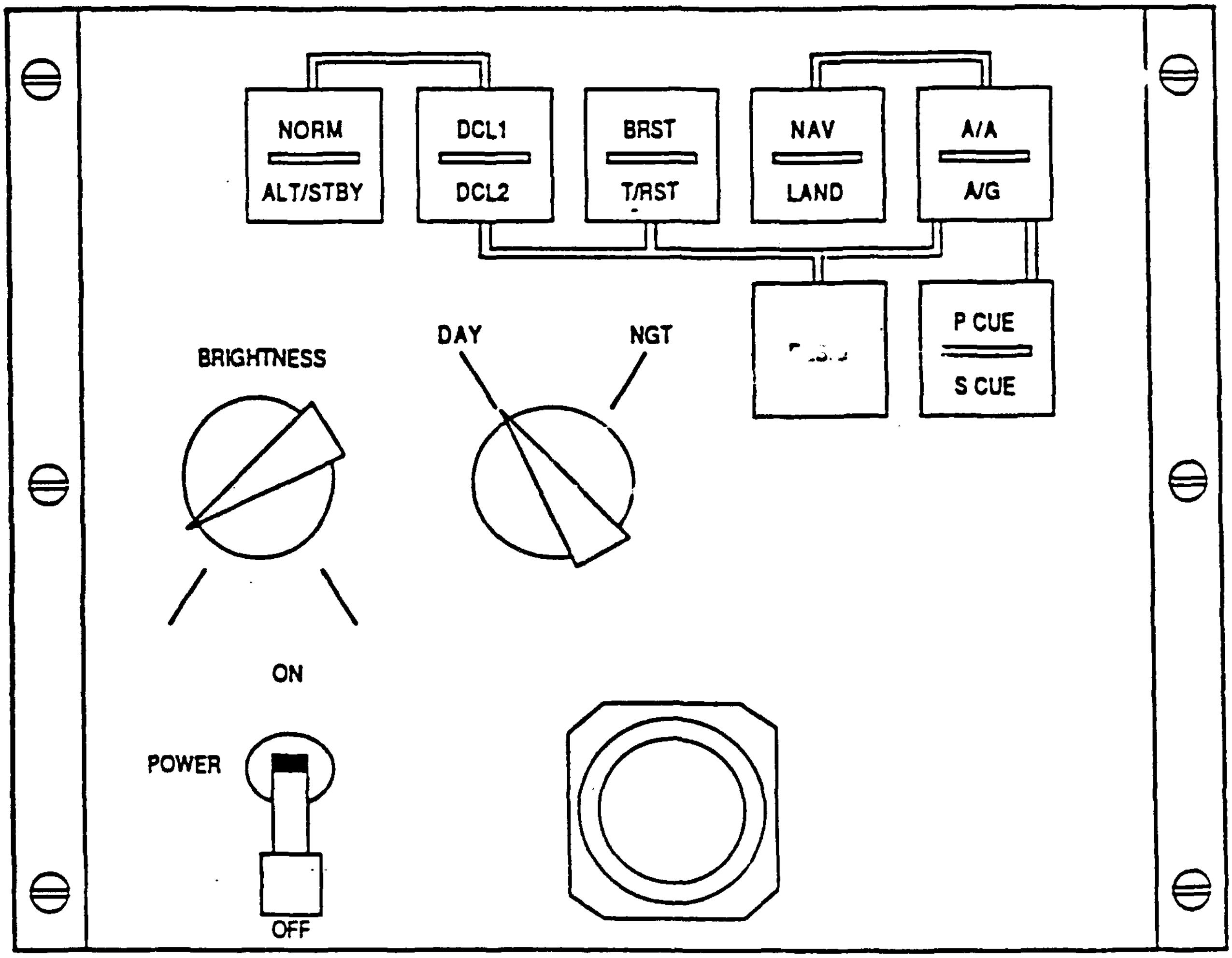

FIGURE A-9. HMD CONTROL PANEL

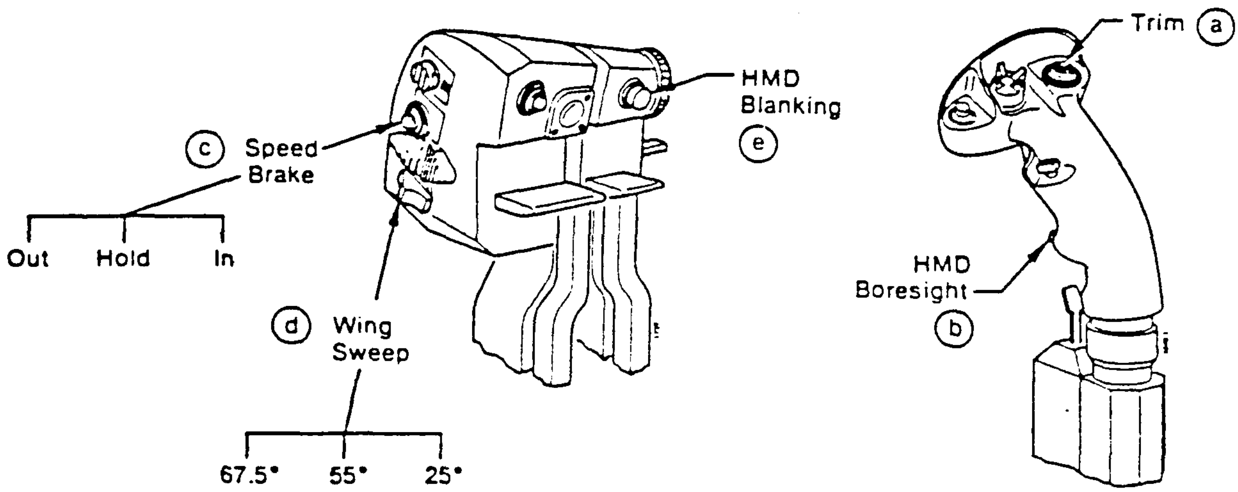

FIGURE A-10. ACTIVE STICKGRIP AND THROTTLE CONTROLS shown in Figure A-11. The pilot's head is positioned so as to align the two symbols visually. When the two are aligned, the Boresight Switch is released.

3.0 Helmet Mounted Display (HMD) Formats

3.1 Basic Display - The basic format, which is present whenever the HMD is on, is shown in Figure A-12. A description of display elements is provided below.

3.2.1 Heading Indication and Scale - The three digit number below the scale at the top indicates aircraft magnetic heading.

3.2.2 Horizon Bar - The location of the real world horizon relative to head orientation is indicated by the horizon bar. It is always drawn parallel to the real horizon. When the real horizon is outside the HMD FOV, the horizon bar will be displayed as a dashed line at the edge of the display FOV, but it will remain parallel to the real horizon. This case is shown in Figure A-13.

The horizon bar employs ground pointers and sky pointers to indicate which side of the bar is down (toward the ground). When the pilot's head is positioned within 6° of aircraft heading, there will be a gap in the bar indicating the direction in which the aircraft is flying. The tick marks on either side of this gap are ground pointers, and indicate which side of the bar is the ground side. As the pilot moves his head to either side, the gap will slide to the edge of the HMD FOV, and will be removed from the display once the 6° point is reached. At this time, a triangle symbol will appear on the opposite side of the HMD, as shown in Figure A-14. This is a sky pointer, and indicates which side of the bar is the sky side. As the pilot's head angle relative to the aircraft nose increases, the triangle will move toward the center of the HMD until 12° is reached. At this time, the triangle will be centered on the horizon bar, and will remain centered until the angle is reduced below 12°. Figure A-14 illustrates the case where the pilot's head is being moved to the right.

It should be noted that the horizon bar indicates horizon location, NOT aircraft attitude. However, the bar does provide an extreme attitude warning, as discussed in paragraph 3.3 below.

3.2.3 Waterline - The "Waterline" symbol indicates the position of the nose of the aircraft relative to the horizon. This symbol is space stabilized to the nose of the aircraft, and will disappear off the display as you move your head away from the nose.

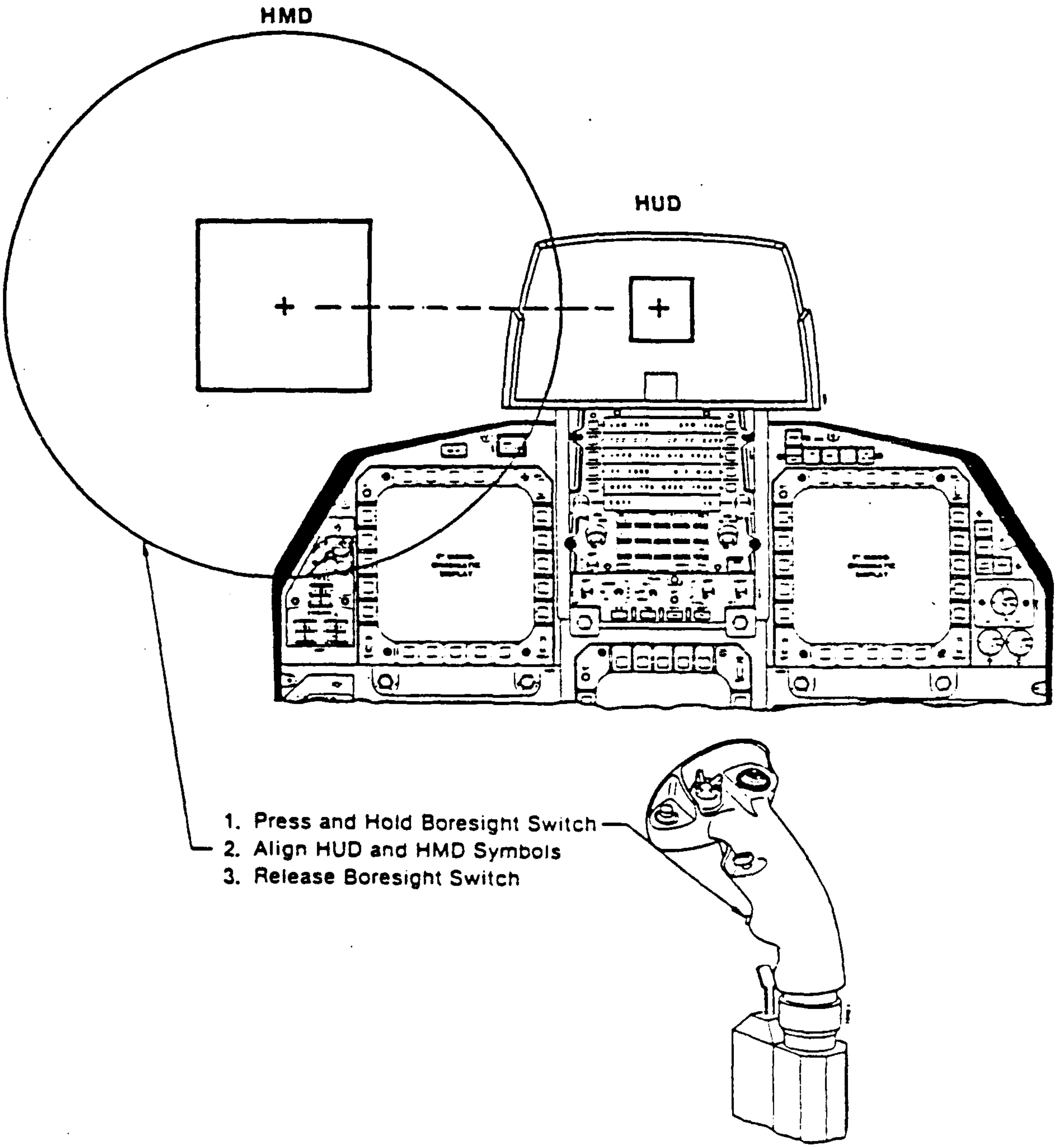

FIGURE A-11. HMD BORESIGHT PROCEDURE

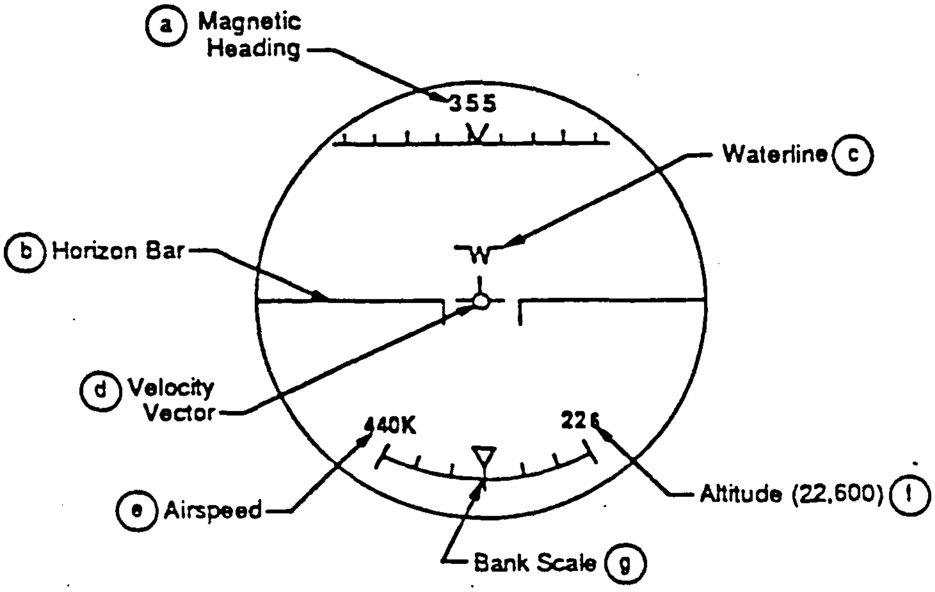

FIGURE A-12. BASIC B-1 HMD FORMAT

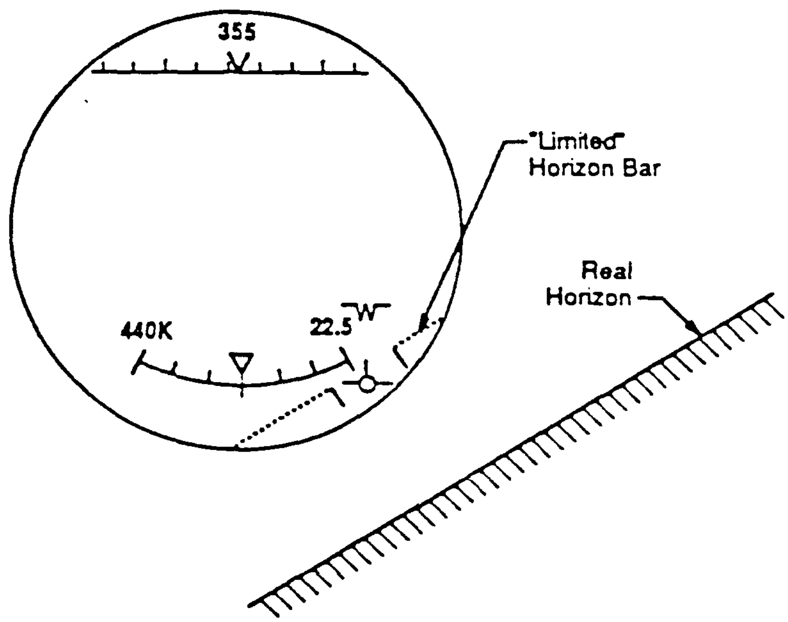

FIGURE A-13. HORIZON OUTSIDE FOV

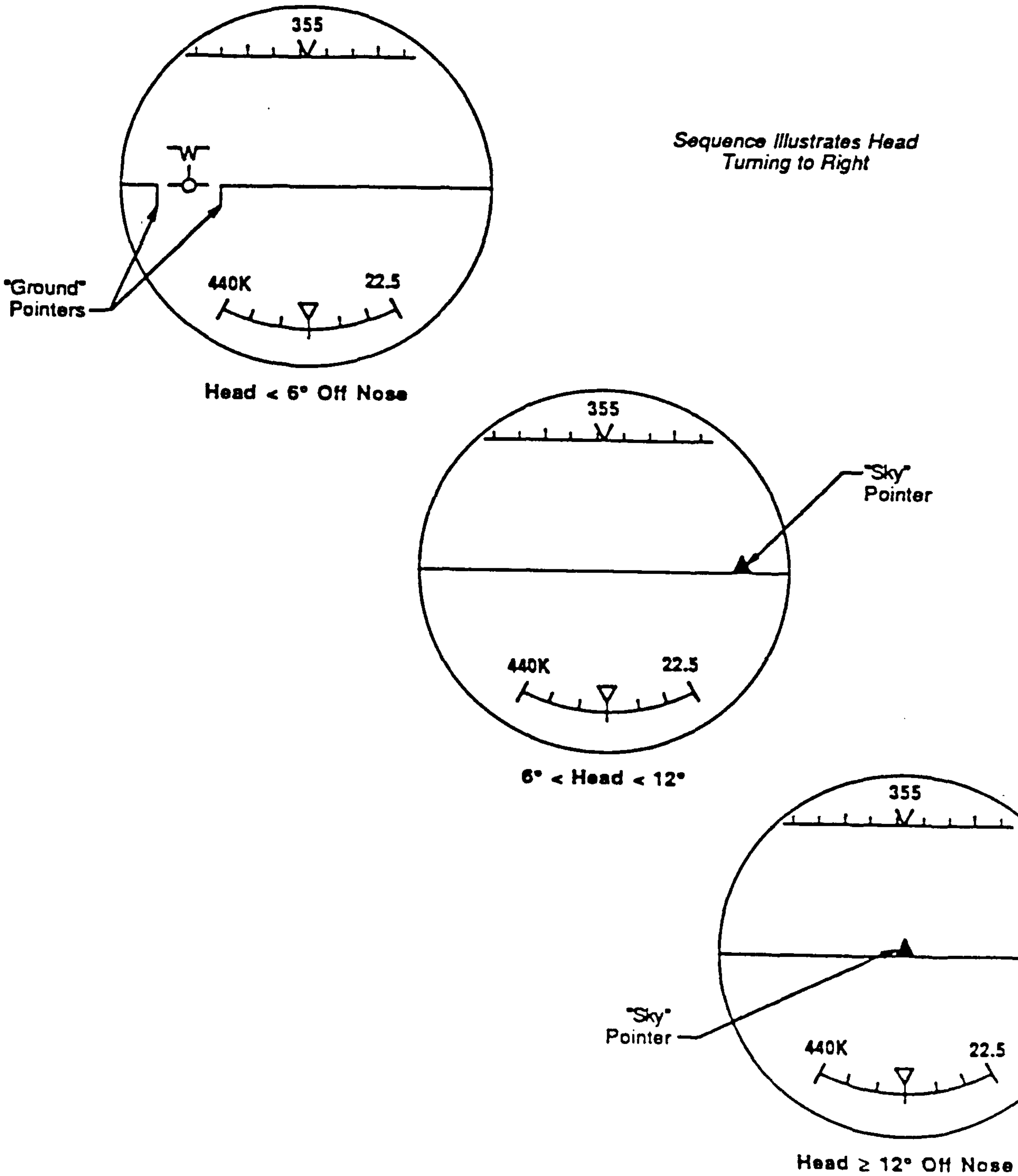

FIGURE A-14. HELMET POINTED AWAY FROM NOSE OF AIRCRAFT

3.2.4 Velocity Vector - The velocity vector indicates the point towards which the aircraft is flying (actual flight path). Thus, if the aircraft is flown so as to place the velocity vector on the horizon bar, the aircraft will be in level flight, maintaining a constant altitude. This will be true regardless of airspeed, angle-of-attack, or aircraft attitude. Note that the velocity vector normally does not coincide with aircraft nose position. The waterline symbol provides aircraft nose position, and it is usually above the velocity vector, reflecting positive angle-of-attack. The velocity vector indicates aircraft flight path as opposed to aircraft pitch attitude.

3.2.5 Airspeed - Airspeed is displayed, to the nearest knot, on the left at the bottom of the display. It is distinguished from altitude by the "K" symbol (knots), which follows the digits. All digits are drawn full size (approximately 5 mils x 7 mils). This display will provide either calibrated airspeed (CAS) or ground speed (GS), depending on the phase of flight. During the tanker rendezvous, CAS will be displayed. During the low level penetration, GS will be displayed.

3.2.6 Mean Sea Level (MSL) Altitude - MSL Altitude is displayed on the right at the bottom of the display. Thousands of feet are displayed as full size digits; hundreds of feet are displayed by a single digit, which is 75% of full size.

3.2.7 Bank Scale - Aircraft bank angle is displayed by the bank scale at the bottom of the display. Tick marks indicate every 10° of bank up to 30° bank left or right. If 30° bank is exceeded, the bank scale pointer will move off the scale and continue until 45° bank is reached. If 45° bank is exceeded, the bank pointer remains "pegged" at 45° flashes.

3.3 Extreme Attitude/Ground Proximity Warning - The system provides a warning of extreme attitudes as a function of ground proximity. The triggering conditions are set for fighter aircraft operations, so you will probably not see this warning. It is provided whenever either set of the following conditions occurs:
A. Dive Angle between 30° and 60°, and altitude at or below 5000 ft. MSL.
B. Dive Angle 60° or greater and altitude at or below 10,000 ft MSL.

When triggered, the horizon bar flashes at 2.5 Hz. These altitude/dive angle combinations provide sufficient altitude for dive recovery with a fighter. No attempt has been made to convert them to B-1 performance.

3.4 Air Target Symbols - When another aircraft is being tracked, one of two symbols will be present on the HMD: the Target Designator (TD), a box positioned at the target's line of sight (LOS); or the Target Pointer (TP), which is an arrow pointing toward the target LOS. Both symbols are illustrated in Figure A-15.

If the target is not located within the HMD FOV, then the TP arrow will be present. The TP arrow radiates out from the center of the HMD FOV at an angle which indicates the shortest direction to the target LOS. By moving his head in the direction indicated, the pilot is moving the helmet to a position which aligns the helmet LOS to the target LOS. This helps the pilot locate the TD box.

The TD box is a square that measures 25 milliradians (mr) on each side. The length of the TP arrow is fixed at 50 mr until the target is within 45° of the helmet LOS. Then, it shortens at a rate of 1 mr/degree, until the target is within the HMD FOV (arrow is approximately 11 mr long). Once the target is within the HMD FOV, the TD box appears around the target, and the TP arrow disappears. The two symbols are mutually exclusive; there is never a situation when both are displayed at the same time.

When the TD box is displayed, closure rate and range to the tracked aircraft is displayed by two numbers. The number above the TD box provides closing velocity in knots. If the relative position of the two aircraft (B-1 and target) is such that they are moving apart, this number is prefixed with a negative sign (-). The number below the TD box indicates range to the target to the nearest 0.1 NM.

The Air Target format will be displayed during the tanker rendezvous. It is assumed that the operation of locating and tracking the tanker is being performed by aircraft systems, and these systems are providing the data necessary to drive the displays.

3.5 Ground Target Symbols - When performing navigation to a ground point, two symbols will be present on the HMD: the waypoint symbol and the command heading marker. Both are depicted in Figure A-16.

The waypoint symbol is a circle 25 mr in diameter that is positioned at the LOS of the waypoint on the ground. The number inside the circle indicates waypoint number (e.g., waypoint 4). The number below the circle provides time-to-go to the waypoint in minutes and seconds. When the waypoint LOS is outside the FOV of the HMD, the

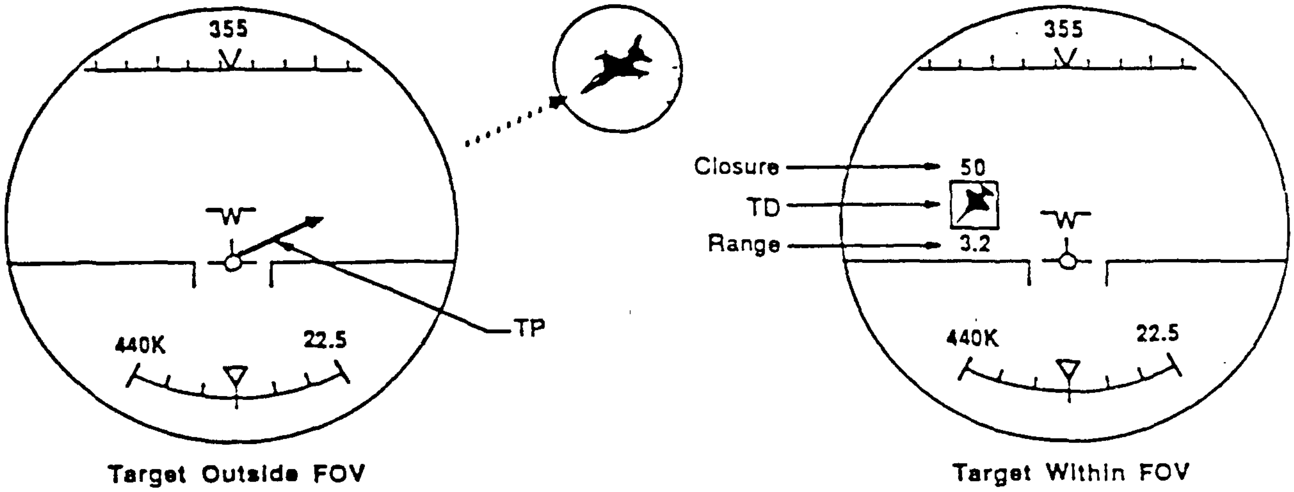

FIGURE A-15. AIRBORNE TARGET DISPLAYS

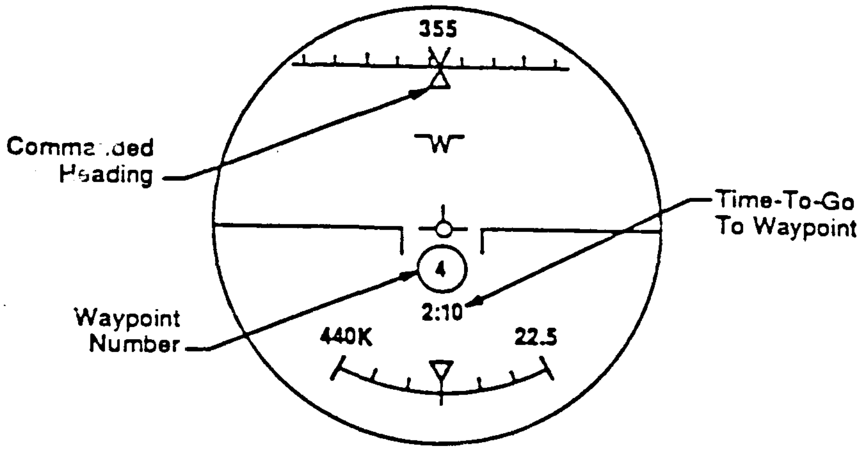

FIGURE A-16. GROUND TARGET DISPLAY

waypoint symbol is limited to indicate the direction to look to find the waypoint. This is shown in Figure A-17. The command heading marker is a small triangle and pointer positioned below the heading scale at the top of the HMD. When aircraft heading is within 4° (approximately) of the commanded heading, the command heading marker will be positioned appropriately on the heading scale. If the aircraft heading is more than 4° different from commanded heading, the command heading marker will be pegged in the direction the aircraft should be turned.

The waypoint symbol and command heading marker always indicate the next waypoint in the mission. The system automatically sequences to the next waypoint on the route when the pilot crosses a waypoint. In this simulation, all turns will be made after crossing the waypoint, as opposed to turning early to intercept a course centerline.

The Ground Target format will be displayed during the low level penetration portion of each run. It is assumed that the OSO performs the necessary operations to supply waypoint location to the aircraft systems, and these systems are providing the data necessary to drive the displays.

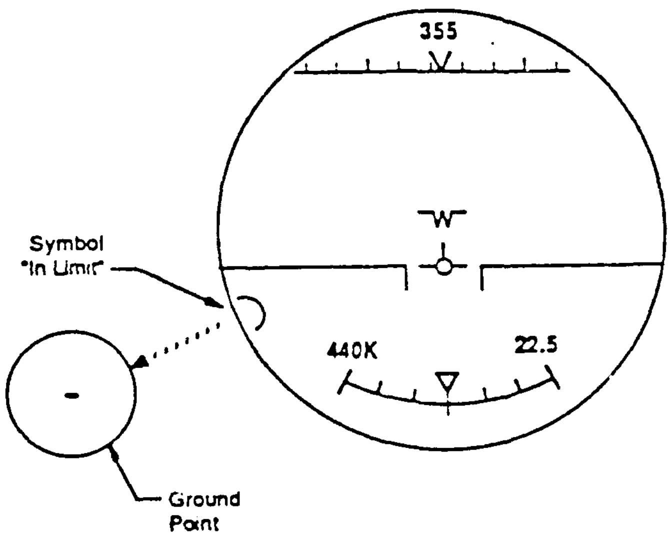

FIGURE A-17. GROUND TARGET OUTSIDE HMD FOV